CONTRIBUTION OF ORGANIC COCOA AGROFORESTRY TO SUSTAINABLE LAND MANAGEMENT

A Thesis submitted to the Department of Agricultural and Environmental Sciences, School of Biosciences, The University of Nottingham for the degree of

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IN
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BY

MICHAEL ASIGBAASE

MSc. (Natural Resources – Sustainable Environmental Management)

BSc. (Natural Resources Management)

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Declaration

I hereby declare that this Thesis submitted for the degree of PhD (Environmental Science) is my own work under supersivion and that it is an original work with no material previously published by another person or accepted for the award of any other degree of the university, except where due acknowledgement has been made in the thesis.

Michael Asigbaase … … ….15/07/2019…
(Student's name) (Signature) (Date)

Certified by:

Dr. Sofie Sjögersten …15/07 2019…
(Supervisor) (Signature) (Date)

Dr. Barry H. Lomax … …15/07/2019…
(Co-supervisor) (Signature) (Date)

Dr. Evans Dawoe … . ….18/07/2019…
(Co-supervisor) (Signature) (Date)

Abstract

This research was undertaken to evaluate the potential of organic and conventional cocoa agroforestry systems in different productive stages (Young, ≤ 15 years; Mature, 16 to 30 years; Old, ≥ 31 years) to contribute to sustainable land management through tree biodiversity conservation, carbon sequestration and nutrient recycling. It also assessed the influence of organic and conventional management of cocoa agroforestry systems on soil physico-chemical properties, cocoa pod production and crop (*Musa spp.*) yield. The study was conducted in the Moist Semi-deciduous Forest Zone of the Eastern Region of Ghana. Cocoa systems under organic management consistently maintained greater shade tree species diversity compared to those under conventional management. Shade tree species richness was higher on organic farms (5.10 ± 0.38) than conventional farms (3.48 ± 0.39). On organic farms, density of food and fruits shade trees (*per* ha) was three-fold (Org. 341 ± 38 vs. Con. 106 ± 18) when compared to conventional farms. Organically managed cocoa agroforestry systems demonstrated a greater potential to sequester and store carbon in the aboveground (39.6 Mg C ha^{-1}), belowground (10.3 Mg C ha^{-1}) and soil (0-30 cm depth, 59.7 Mg C ha^{-1}) pools compared to conventionally managed cocoa systems (22.1 Mg C ha^{-1}, 7.1 Mg C ha^{-1}, 49.7 Mg C ha^{-1}, respectively). The rate of total carbon storage (vegetation plus soils) ranged from 3.4 Mg C ha^{-1} yr^{-1} (young cocoa systems) to 9.0 Mg C ha^{-1} yr^{-1} (old cocoa systems) in the organic systems and 1.1 Mg C ha^{-1} yr^{-1} (young cocoa systems) to 4.9 Mg C ha^{-1} yr^{-1} (old cocoa systems) on conventional farms. Annual litterfall (Org. 12.4 Mg ha^{-1} yr^{-1} vs. Con. 12.7 Mg ha^{-1} yr^{-1}) and nutrient deposition through litterfall were similar on both organic and conventional cocoa farms. The contribution of shade tree species to nutrient return via litterfall was more pronounced in organic systems than conventional systems. Organic cocoa farms had a greater rate of leaf litter decomposition (k = 1.9) than conventional cocoa systems (k = 1.3). Similarly, the rate of macro- and micro-nutrient mineralization was consistently greater on cocoa farms under organic management compared to those under conventional management. The time required for 99% mineralization of nutrients (t_{99}) in leaf litter ranged from 1.30 (Fe) to 2.22 years (Ca) on organic cocoa farms versus 1.84 (K) to 3.22 years (Ca) on conventional cocoa farms. Organic management enhanced the physico-chemical properties of soils compared to conventional management; soil moisture content and electrical conductivity were consistently greater on organic cocoa systems than conventional cocoa systems. Similarly, organic farms had significantly higher stocks of P (51.0 kg ha^{-1}), Mn (310 kg ha^{-1}) and Cu (0.4 kg ha^{-1}) at the 0-30 cm depth compared to conventional farms (28.1 kg ha^{-1}, 165 kg ha^{-1} and 0.1 kg ha^{-1}, respectively). Annual cocoa pod production *per* tree was similar for both organic and conventional farms (10 pods *per* tree for both farm types). However, the overall cocoa pod production was greater on conventional farms (12,433 ha^{-1} yr^{-1}) than organic farms (9,560 ha^{-1} yr^{-1}) due to greater cocoa tree density (Org. 1012 ± 40 stems ha^{-1} vs. Con. 1203 ± 40 stems ha^{-1}). The annual production of banana (*Musa sapientum* L. f. thomsonii King ex Baker) and plantain (*Musa paradisiaca* L.) was significantly greater in organic cocoa systems (186.3 kg ha^{-1} yr^{-1}) than conventional systems (31.6 kg ha^{-1} yr^{-1}). The results emphasize the potential of smallholder organic cocoa systems to ensure environmental sustainability and long-term cocoa productivity. The adoption of organic management in smallholder cocoa systems is therefore recommended.

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I dedicate this thesis to my lovely wife, lively kids and supportive parents.

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ANOVA	Analysis of variance	
COCOBOD	Ghana Cocoa Board	
Con	Conventional	
C/N	Carbon to nitrogen ratio	
DBH	Diameter at breast height	cm
ECEC	Effective cation exchange capacity	cmolC kg^{-1}
FAO	Food and Agriculture Organization	
FAOSTAT	FAO Statistics	
GDP	Gross Domestic Product	
GMO	Genetically Modified Organisms	
ha	Hectare	
ICCO	International Cocoa Organization	
ISU	International Sustainability Unit	
IFOAM	International Federation of Organic Agriculture Movements	
IUCN	International Union for Conservation of Nature	
IVI	Importance Value Index	
k	Annual decay rate constant	
kg	kilogram	
LSD	Least Significant Difference	
MCS	Mature cocoa systems	
Mg	Mega-gramm (ton)	
mg	milligram	

MoFA	Ministry of Food and Agriculture
OCS	Old cocoa systems
Org	Organic
REDD+	Reduced Emissions from Deforestation and Forest Degradation, plus the sustainable management of forests, and the conservation and enhancement of forest carbon stocks
SEM	Standard error of mean
SOC	Soil organic carbon
SOM	Soil organic matter
UN DESA	United Nations Department of Economic and Social Affairs
USDA	United Nations Department of Agriculture
YCS	Young cocoa systems

1 INTRODUCTION

1.1 Background

Agriculture has historically shaped our world and continues to do so. It is estimated that nearly 38% of the surface of the Earth is dedicated to food production, thus agriculture is the largest human land use (Foley, 2011). Agricultural expansion and intensification have improved the quality of life of millions of people worldwide, serving as a major source of livelihood and the mainstay of the economy of many developing countries (Hütz-Adams *et al.*, 2016; Kroeger *et al.*, 2017). However, this has come at the cost of the environment. The expansion of agricultural systems is a major driver of deforestation and native habitat loss, especially in forest-rich countries and biodiversity hotspots (Kroeger *et al.*, 2017). The continuing loss of biodiversity and soil nutrients have been linked to agricultural expansion and intensification (Vaast and Somarriba, 2014; Wilson and Lovell, 2016). Moreover, agriculture remains a major contributor to anthropogenic climate change through the emission of greenhouse gases (Forley, 2011; Vermeulen *et al.*, 2012). As the world’s population is estimated to increase to 8.6 billion by 2030 and to 9.8 billion by 2050, there is an urgent need to promote land use systems which meets both productivity and environmental needs (UN DESA, 2017), via sustainable land management.

1.2 Sustainable land management

Sustainable land management in the context of agriculture can be defined as using and managing agricultural land in a manner that meets present needs without compromising its potential to meet future needs (Alemu, 2016; Wilson and Lovell, 2016). In other words, sustainable land management means producing food whilst conserving the environment. Therefore, the maintenance of biodiversity, soil fertility and quality, and carbon storage as well as its attendant climate change mitigation are essential aspects of sustainable land management (Wilson and Lovell, 2016). Sustainable land management reconciles the objectives of intensified economic and social development with the objectives of sustaining and intensifying the ecological roles of land resources (Alemu, 2016). Organic farming is emerging as a sustainable land management approach, especially for Africa whose economy is majorly dependent on rain-fed agriculture which is vulnerable to climate change (Badgley *et al.,* 2007; FAO, 2011; Nunoo *et al.,* 2014; Barrios *et al.*, 2015; Jacobi *et al.*, 2015)

1.3 Organic farming

Organic farming is governed by internationally accepted standards based on cultivation, pest and weed control, and animal husbandry approaches set out by the International Federation of Organic Agriculture Movements (IFOAM). IFOAM (2008) defines organic agriculture as a farming system that ensures and enhances the health of the environment as a unit and prohibits the use of synthetic agrochemicals, food additives and Genetically Modified Organisms (GMO). The non-use of synthetic chemicals such as fertilizers, pesticides, herbicides and preservatives seek to sustain and enhance the health of people, soils and ecosystems (IFOAM, 2010). Organic farming, therefore, relies solely on ecological processes and cycles as well as biodiversity to meet productivity needs in a manner that seeks to benefit the environment, promote fairness and provide quality life for all (Glin *et al.,* 2015; Djokoto *et al*., 2016; Wilson and Lovell, 2016). Thus, organic farming is founded on four principles; health, ecology, fairness and care (Figure 1.1). It emphasizes the use of management practices (e.g. cultural and biological methods) adapted to local conditions rather than off-farm inputs such as fertilizers (IFOAM, 2008; 2010). Soil fertility and quality are maintained through practices such as cover cropping, mulching, applications of manure and compost, use of leguminous plants and crop rotation (USDA, 2015) whereas pests and weeds are controlled by the use of resistant varieties, providing habitats for beneficial predators and weeding (USDA, 2015).

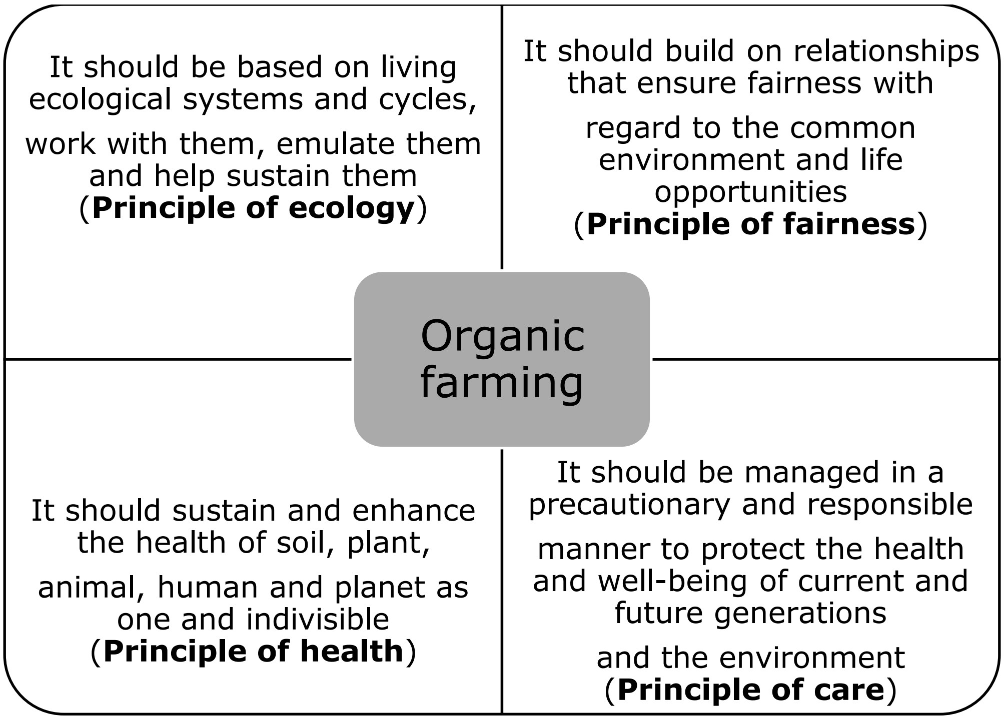

Figure 1.1 Principles of organic farming (Adapted from: Djokoto *et al*., 2016)

1.4 Organic versus conventional cocoa farming

In West Africa and elsewhere, cocoa is mostly cultivated as an understorey crop together with food crops in the shade of large forest trees forming a complex multi-structural agroforestry system (Gockowski and Sonwa, 2011; FAO, 2017). However, recently, cocoa plantations with no shade trees or shade provided by a single tree species have been introduced and promoted, especially in forest-rich West Africa where 70% of the world’s cocoa are produced (Wessel and Quist-Wessel, 2015). These simplified cocoa systems require many more external inputs such as fertilizers and pesticides than the complex multi-structural cocoa systems (Vaast and Somarriba, 2014; Hütz-Adams *et al.*, 2016). In Ghana, over

50% of the estimated 1.63 million ha of cocoa farms depend mainly on nutrient recycling to sustain productivity because farmers lack the capacity to access and/or purchase synthetic agrochemicals (Barrientos *et al.*, 2008; IFDC, 2012; Gockowski *et al.*, 2013). That is, cocoa farming necessarily originated as an organic system and a significant proportion persists as it is the case for most agricultural systems in developing countries (Djokoto *et al*., 2016), but organic certification is a recent phenomenon.

The adoption of organic farming principles in cocoa production by over 5,000 farmers in Ghana has led to production practices that contrast with conventional cocoa production practices, differing based on planting, weed, pest and disease control (Table 1.1; Glin *et al.,* 2015; Djokoto *et al*., 2016). Whereas organic famers rely solely on organic inputs (e.g. manure) and nutrient recycling to replenish nutrient loss through cocoa production, and shade management to supress weeds, pests and diseases (Barrientos *et al.*, 2008; Djokoto *et al*., 2016), conventional cocoa systems rely on synthetic chemical fertilizers and pesticides. Moreover, agrochemical usage has been linked to shade tree removal in cocoa systems in Ghana (Nunoo *et al.,* 2014). Thus, whereas conventional cocoa farmers may intensify cocoa production by replacing shade trees with cocoa and using more agrochemicals, the organic farmers are encouraged to retain and manage shade trees as a cheaper and more sustainable approach to replenishing soil nutrients and diversifying output.

Table 1.1 Organic and conventional cocoa cultivation practices (Djokoto *et al.*, 2016).

Practice	**Organic practices**	**Conventional practices**
Planting	• Spacing: 3 × 3 m • Seedlings from only organic nurseries	• Spacing: 3 × 3 m. • Seedlings from clean nurseries or planting at stake
Weed control	• Weed regularly manually. • Use cover crops • No chemical weed control	• Manual weed control • Use of cover crops • Use recommended chemicals
Pest and disease control	• Remove mistletoes, dead branches and black pods.	• Remove mistletoes, dead branches and black pods
	• Collect and burn away from the farm diseased pods once a week to prevent spread of black pod disease. • When necessary to bury on the field, bury 60 cm deep. • Remove pods with even small sign of black pod attack	• Collect and burn away from the farm diseased pods once a week to prevent spread of black pod disease. • When necessary to bury on the field, bury 60 cm deep. • Remove pods with even small sign of black pod attack. • Apply recommended chemicals. Dosage 85–500 ml/ha depending on pesticide
	• Spray with Neem tree extract when sanitation practices are inadequate • Apply 40 ltrs/ac = 3 mistblowers/acre	
	• Wear protective clothing	• Wear protective clothing
	• Other permitted products can be used	
Fertility management	• Improve fertility with use of cover crops, leguminous plants, compost making, farm yard manure and planting shade trees. • Other permitted products can be used	• Apply NPK fertilisers such as Asaase Wura and Cocofeed. • Others are triple super phosphate and ammonium sulphate

Certified organic cocoa agroforestry can be defined as the production of cocoa in accordance with agreed-upon standards for organic agriculture of which the inclusion of trees is encouraged or required (IFOAM, 2010; Glin *et al.,* 2015). Farmers comply with standards produced and enforced by both government and private institutions based on IFOAM standards, gain full certification after a period of three years and they are regularly monitored to ensure continual compliance by the certifying body (Djokoto *et al*., 2016).

1.5 Ecological importance of cocoa agroforestry systems

1.5.1 Provision of natural habitats, buffer zones and corridors

The potential for biodiversity conservation in shaded cocoa agroforests has been demonstrated, even at the landscape level (Clough *et al.*, 2011; Daghela Bisseleua, 2013; Leakey, 2014). Asare *et al.* (2014) reported that cocoa agroforests with diverse shade tree species could serve as corridors and increase connectivity between forests fragments. Similarly, Daghela Bisseleua *et al.* (2013) concluded that cocoa agroforests not only support biodiversity, but these systems serve as links between forest fragments for migratory fauna. In Indonesia, a study conducted by Clough *et al.* (2011) revealed that shade cover of 40-60% conserves biodiversity and ensures sustainability in cocoa agroforests without significantly affecting cocoa yields. In addition, Cameroonian multi-strata cocoa agroforestry systems contribute to long-term conservation of tree species facing a conservation issue (Saj *et al.,* 2017). In an earlier study in Cameroon, Daghela

Bisseleua *et al.* (2013) documented 102 tree species (belonging to 56 families), 260 herbaceous species (belonging to 113 families) and 38 species of ants in studied cocoa agroforestry systems. Therefore, diverse and multi-layered cocoa agroforests can be important reservoirs for biodiversity and may potentially serve as buffer zones and corridors around protected areas and forest fragments, but this potential is partly regulated by management.

1.5.2 Control of insect pests

Daghela Bisseleua *et al.* (2013) documented the role of ants in controlling pests in cocoa plantations and their role for other predators in agroforestry systems. According to Klein *et al.* (2002), cocoa monocultures host more insect pests and fewer natural predators, thus stands a higher risk of pest outbreak compared to diverse agroforests. For example, the African capsid (*Distantiella theobroma*) is an economic pest of cocoa in Ghana promoted by shade reduction or removal (Flood *et al.,* 2004). In Puerto Rican coffee farms, Borkhataria *et al.* (2006) revealed that lizards and birds controlled the presences of pests such as coffee leafminers (*Leucoptera coffeella*) and flatid planthoppers (*Petrusa epilepsies*) probably because of the presence of shade trees. Diverse flora and fauna in agroforestry systems such as cocoa agroforests, have functional consequences and augment ecosystem services like natural pest control (Leakey, 2014). Consequently, cocoa agroforests, which maintain shade tree species richness and diversity, are more resilient to pest compared to simplified or monocultural systems (Soto-Pinto *et al.,* 2002; Leakey, 2014; Jacobi *et al*., 2015).

1.5.3 Carbon sequestration

Cocoa agroforestry is an acknowledged means of carbon sequestration, but its potential is dependent on the management approach adopted by cocoa farmers (Somarriba *et al.*, 2013; Asase and Tetteh, 2016; Dawoe *et al.*, 2016; Mohammed *et al.*, 2016). For example, one hectare of diverse cocoa agroforests can sequester 5 to 10 times the carbon sequestered in one hectare of monocultural cocoa systems (Mohammed *et al.*, 2016; Rajab *et al.*, 2016). Furthermore, Jacobi *et al.* (2014) reported significantly lower aboveground carbon stocks in monocultural cocoa systems compared to both simple and diverse cocoa systems. In Ghana, Asase *et al.* (2008) reported carbon storage of 224.1 Mg C ha^{-1}, 155.1 Mg C ha^{-1} and 71.9 Mg C ha^{-1}, respectively, for remnant forest, traditional shaded cocoa farms with native tree species and un-shaded intensive cocoa farms.

1.5.4 Water quality and quantity

Cocoa agroforests improve the quality and quantity of water in two ways; through increased soil water-holding capacity and/or reduced use of agrochemicals. The shade tree component of cocoa agroforests retain rainfall, reduce surface run-off, nutrient losses and loss of soil (Ranieri *et al.,* 2004). Furthermore, the soils of cocoa agroforestry systems are usually not cultivated (i.e. zero tillage or reduced tillage) and are covered with accumulated litter from cocoa and shade trees which increases organic matter contents, enhances the water holding capacity of soils and reduces stress due to drought (Verchot *et al*., 2007; Dawoe *et al.*, 2010; Kyereh, 2017). According to Rice (2010), nitrogen-fixing shade trees in agroforestry systems can add up to 100 kg ha^{-1} yr^{-1} of nitrogen and consequently reduce fertilizer requirement by 25-30%. Furthermore, Soto-Pinto *et al.* (2002) reported a positive correlation between spontaneous weed growth and reduction of shade density and this means reduced need for synthetic herbicides in well-shaded agroforestry systems. Reduced use of agrochemicals may contribute to improving water quality through reduced leaching and runoff of such chemicals into water bodies (Udawatta *et al.*, 2002).

1.5.5 Soil quality and protection

Agroforestry systems like coffee and cocoa agroforests can conserve and protect soil through soil stabilization and maintenance of soil moisture during drought or dry seasons (Rice, 2010; Kyereh, 2017). Verchot *et al.* (2007) suggested agroforestry as a tool for climate change adaptation in the humid tropics because the roots of shade trees bind soils together, enhance soil stability and reduce soil erosion and landslides. For instance, soil erosion in Indonesian alley cropping (strips of trees alternating with coffee) farms with shade trees was reduced by 64% compared to farms without shade trees (Rice, 2010). Ranieri *et al.* (2004) asserted that the tree component of agroforestry systems reduces the impact of heavy rainfall on soil through increased rainfall interception and reduced drip damage from leaves. Therefore, diverse agroforestry systems protect soil and improves soil quality through mitigation of soil erosion.

A more diverse tree component also retrieves nutrients leached beyond the reach of cocoa trees and makes them available to plants through litterfall and decomposition (Dawoe *et al.*, 2010; Kaba, 2017), thereby contributing significantly to mitigation of soil degradation. In a study conducted by Asase *et al.* (2008) in Ghana, decomposition of litter from studied cocoa agroforestry systems released 90% of N, 90% of P and 93% of K into the soil over a 12-month period for shaded systems and a release of 75% of N, 66% of P and 88% of K in unshaded systems over the same period. This indicates that agroforestry systems have the potential to improve soil quality. Furthermore, nitrogen fixation by shade trees on cocoa farms improve soil N-status. For instance, Kaba (2017) reported an input of 22-51 kg N ha^{-1} yr^{-1} through nitrogen fixation by *Gliricidia sepium* (Jacq. Kunth ex Walp) planted at 124 trees ha^{-1} for shade provision in agroforestry systems in Ghana. Similarly, Rice (2010) reported up to 145 kg ha^{-1} yr^{-1} of nitrogen fixation by Erythrina *spp.* in coffee systems.

1.6 Problem statement, rationale and justification

1.6.1 Low cocoa yields

The potential yield of cocoa in Ghana is estimated to be in the region of 1,500-2,000 kg ha^{-1} (Aneani and Ofori-Frimpong, 2013).

Although cocoa yield in Ghana has steadily increased from 300,000 tonnes in 1995 to 900,000 tonnes in 2014 (Wessel and Quist-Wessel, 2015; FAO 2017), the average yield *per* ha (400 kg) has remained low compared to yields of 800 kg ha^{-1} in neighbouring Cote d'Ivoire, 1000 kg ha^{-1} in Indonesia, and 1800 kg ha^{-1} in Malaysia (Wessel and Quist-Wessel, 2015; Kongor *et al.*, 2018). Moreover, the national average is even lower than the estimated world average of 500 kg ha^{-1} (Hütz-Adams *et al.*, 2016), suggesting that Ghana's place as a key cocoa producer and exporter is majorly as a result of cocoa expansion (Vaast and Somarriba, 2014; Kongor *et al.*, 2018) at the expense of existing forests (Wessel and Quist-Wessel, 2015; Benefoh, 2018).

The low yields have been attributed to several factors such as soil nutrient depletion (Kaba, 2017), pests and diseases (Aneani and Ofori-Frimpong, 2013; Hütz-Adams *et al.*, 2016), changing climatic conditions (Gockowski *et al.*, 2013; Schroth *et al.,* 2016), poor shade management practices (Kongor *et al.*, 2018), over-aged farmers and cocoa plantations (Wessel and Quist-Wessel, 2015; Benefoh, 2018), and planting of low-yielding cocoa varieties (Kongor *et al.*, 2018). The government of Ghana through COCOBOD (the governmental body responsible for regulating the cocoa sector) has introduced several interventions such as free pest and disease control programmes and the introduction of packages of hybrid seeds, fertilizers, insecticides and fungicides with the aim of closing this yield gap (Wessel and Quist-Wessel, 2015; Gockowski *et al.*, 2013). While these interventions raise environmental concerns due to their potential to drive pollution, loss of biodiversity and environmental degradation, there are also questions about their sustainability (Hütz-Adams *et al.*, 2016; Benefoh, 2018; Kongor *et al.*, 2018).

1.6.2 Cocoa driven deforestation and limited area for expansion

According to FAO (2010), agricultural and industrial expansion has led to the loss of 60% (2.7 million ha) of the original primary forest cover in Ghana. Deforestation in Ghana remained at 311,880 ha *per* year from 2001 to 2011 and has risen to 524,489 ha *per* year since 2012 (Forestry Commission, 2017). As a result, most of the forest reserves and off-reserves, including the Eastern Guinean forest zone in Ghana, are either degraded or significantly depleted (FAO, 2010; Forestry Commission, 2017). Between 2000 and 2014, the area of cocoa cultivation expanded by 12% and cocoa systems replaced 1.6 million ha of forests (FAOSTAT, 2016). Benefoh (2018) reported a 38% decline in forest area from 1990 to 2015 and an increase in cocoa cultivation area by 23% in the Western region of Ghana, the region that harbours the last remaining intact forests in the country. Thus, the steady expansion of the cocoa sector in Ghana comes at an environmental cost. Moreover, there exist limited secondary forests for future cocoa establishment as production frontiers have already moved through the entire cocoa ecological zone in Ghana (Benefoh, 2018).

1.6.3 Unsustainable cocoa intensification

Intensification of cocoa agroforestry systems is on the increase in Ghana (Asare *et al.*, 2014; Nunoo *et al.*, 2014; Dawoe *et al.,* 2016; Kaba, 2017; Benefoh, 2018). Generally, although the intensified cocoa systems produce short term gains in terms of cocoa yield, such systems have significant negative environmental and social consequences (Asase *et al.,* 2008). Intensification of cocoa production systems reduces plant species richness and the diversity of ants, spiders and wasps and promotes recruitment of non-forest tree species (Asase *et al.,* 2008; Daghela Bisseleua *et al.,* 2013). In addition, intensive cocoa systems are also less efficient in terms of nutrient cycling compared to shade or traditional cocoa systems (Dawoe *et al.*, 2010) and may not be sustainable in the long-run without agrochemicals such as fertilizer for nutrient supplement and fungicides for pest control (Nunoo *et al.*, 2014). With intensification, leaching of chemicals into water bodies resulting in water pollution is inevitable (Wlison and Lovell, 2016).

Moreover, rural smallholder farmers produce almost all of Ghana's cocoa (Benefoh, 2018). These farmers often cannot meet the demand for agrochemicals in the long-run due to factors such as financial challenges (Nunoo *et al.*, 2014) and are therefore likely to encroach on forests which results in reduced forest cover and loss of biodiversity (Benefoh, 2018). There is also a loss of ecosystem benefits such as provision of food, medicine, traditional construction material and fuelwood in intensive systems (Rice, 2010; Negash,

2013) which can lead to increased pressure on protected areas for such services. Again, agricultural intensification encourages the use of agrochemicals that may negatively modify soil biota composition, which affects soil health that underpins productivity (Barrios *et al.*, 2015). Therefore, intensification of cocoa production systems can promote degradation of essential ecological services such carbon sequestration and nutrient recycling.

1.6.4 Changing climatic conditions

Cocoa production both contributes to, and is affected by, climate change (Läderach *et al.*, 2011; FAO, 2010). Cocoa is sensitive to drought (Wood and Lass, 2001), thus rising temperature due to climate change could shrink suitable cocoa cultivation areas in Ghana and elsewhere (Läderach *et al.*, 2011; Schroth *et al.*, 2016). In the West African cocoa belt, whereas areas with minimal to intermediate climatic suitability for cocoa production are expected to increase, areas with optimal climatic conditions are expected to reduce by 50% between the present and 2050s climates based on climate prediction models due to increasing drought conditions (Schroth *et al.*, 2016). Moreover, severe droughts significantly reduce cocoa yields in West Africa and increases mortality of cocoa seedlings during the dry season (Schroth *et al.*, 2016).

1.7 Justification for research

Faced with the environmental challenges of cocoa expansion and intensification coupled with the changing climatic conditions, there is the need to promote cocoa systems with the potential to produce cocoa and sustain the environment (Asare *et al.*, 2014; Rajab *et al.*, 2016; Wlison and Lovell, 2016; Saj *et al.,* 2017). Synthesis of research work from other cropping systems suggests that organic farming has the potential to increase yields by up to 80% in developing countries (Badgley *et al.,* 2007). Therefore, it has been suggested that integrating organic farming practices into cocoa agroforestry would enhance sustainable cocoa production (FAO, 2011; Bandanaa *et al.*, 2014; Barrios *et al.*, 2015; Jacobi *et al.*, 2015). It is believed that the non-use of synthetic agrochemicals would induce cocoa farmers to use a greater density and variety of shade trees to replenish soil nutrients through litter decomposition and this will improve tree diversity, carbon sequestration, nutrient recycling and soil quality (Bandanaa *et al.*, 2014; Jacobi *et al.*, 2015; Blanco-Canqui *et al.*, 2017), but robust data supporting such claims are generally lacking, especially in West Africa (Niggli *et al.*, 2008; Scialabba and Muller-Lindenlauf, 2010).

Moreover, the cocoa sector has been included in the nation's carbon accounting budget (Dawoe *et al.*, 2016; Mohammed *et al.*, 2016) and data on all cocoa systems, including organic cocoa, are needed to develop a comprehensive national carbon accounting strategy in line with so-called Readiness Plan Proposal. Based on Ghana's definition of forest under REDD+ (i.e. Reducing Emissions from Deforestation and Forest Degradation plus the sustainable management of forests, and the conservation and enhancement of forest carbon stocks) as at least 1 hectare of trees with a minimum canopy cover of 15% and minimum height of 5 m, cocoa systems in general and organic cocoa systems in particular may play a role in REDD+ interventions but sufficient data is needed to substantiate this.

Finally, as part of the efforts to halt deforestation, a zero-deforestation-cocoa approach was advanced in 2017 and key players such as cocoa and chocolate companies and International Sustainability Unit (ISU) have pledged to work with governments of cocoa producing countries to stop deforestation and degradation through the development and implementation of a joint framework (Prince of Wales, 2017). In order to achieve this critical and ambitious goal, there is an urgent need to assess the impact of organic and conventional management of cocoa systems on soil quality, tree diversity, nutrient recycling and carbon storage in order to understand their potential to sustain cocoa production.

1.8 Research questions

Work presented in this thesis aimed to address these questions:

- Do shade tree species richness and diversity differ between organic and conventional cocoa plantations, and what is the ecological importance value of shade tree species?
- How much carbon is stored in the vegetation and soils of organic and conventional cocoa plantations?

- What is the quantity of litter produced in organic and conventional cocoa plantations, and what are the potential nutrient dynamics in these systems?
- Are there differences in soil quality and yield in organic compared to conventional plantations?

1.9 Research aims and objectives

The study sought to provide data on the potential of organic cocoa agroforestry systems to contribute to sustainable land management. Specifically, the objectives of the research were to:

- determine and compare the floristic composition, diversity and stand structure of conventional and organic cocoa agroforestry systems and evaluate the role these systems play in the conservation of native trees and shrubs (Chapter 2);
- quantify and compare the C stocks in cocoa and shade trees biomass, litter and soil in conventional and organic cocoa agroforestry systems (Chapter 3);
- quantify litter fall production and potential nutrient returns of the cocoa agroforestry systems under evaluation (Chapter 4);
- determine and compare the rate of leaf litter decomposition and nutrient mineralization in the two systems (Chapter 5);

- assess the physico-chemical properties of soils and evaluate cocoa and banana yields under the two management systems (Chapter 6).

1.10 Organization of the study and thesis

The present study analysed how indigenous organic and conventional cocoa agroforestry systems in Ghana contribute to the conservation of native flora (trees plus shrubs) and accumulation of ecosystem carbon stocks. It further evaluated soil physico-chemical properties, crop yield and litter production, decomposition and nutrient mineralization in the two systems (Figure 1.2).

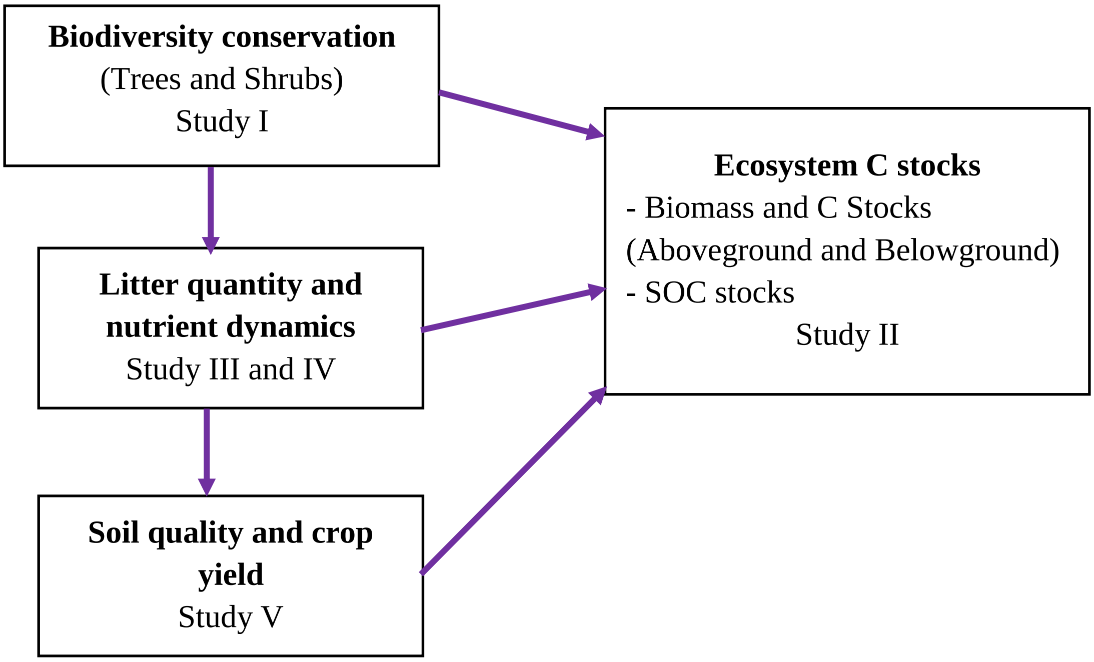

Figure 1.2 Organization of research studies and linkage

In this thesis, each data Chapter (2-6) is written as a manuscript. In Chapter 2, data on floristic composition and diversity of the agroforestry systems (organic versus conventional) are presented and discussed. Existing allometric equations derived for similar ecosystems were used to determine carbon stocks (vegetation plus soil) in the two systems (Study II) using the inventory data from Study I, litter data from Study III and soil data from study V; the results are presented and discussed in Chapter 3. Chapter 4 presents data on litterfall and nutrient contents of shade tree species and cocoa inventoried in Study I; thus, it discusses results from Study III. Leaf litter decay and nutrient return to the soil were assessed in Study IV and discussed in Chapter 5. Crop yield (banana and cocoa pod production) and soil quality (physico-chemical properties) in the two systems were evaluated in Study V and discussed in Chapter 6. The last Chapter (7) covers general discussion, recommendations and conclusions. The potential of the systems under investigation to sustain the environment whilst producing cocoa is explored in Study I to V.

2 TREE DIVERSITY AND ITS ECOLOGICAL IMPORTANCE VALUE IN ORGANIC AND CONVENTIONAL COCOA AGROFORESTS IN GHANA

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Abstract

Cocoa agroforestry systems have the potential to conserve biodiversity and provide environmental or ecological benefits at various nested scales ranging from the plot to ecoregion. While integrating organic practices into cocoa agroforestry may further enhance these potentials, empirical and robust data to support this claim is lacking, and mechanisms for biodiversity conservation and the provision of environmental and ecological benefits are poorly understood. A field study was conducted in the Eastern Region of Ghana to evaluate the potential of organic cocoa agroforests to conserve native floristic diversity in comparison with conventional cocoa agroforests. Shade tree species richness, Shannon, Simpson's reciprocal and Margalef diversity indices were estimated from 84 organic and conventional cocoa agroforestry plots. The species importance value index, a measure of how dominant a species is in a given ecosystem, and 'conservation status' were used to evaluate the conservation potential of shade trees on studied cocoa farms. Organic farms manifested higher mean shade tree species richness (5.10 ± 0.38) compared to conventional farms (3.48 ± 0.39). Similarly, mean Shannon diversity index, Simpson's reciprocal diversity index and Margalef diversity index were significantly higher on organic farms compared to conventional farms. Importance value indices inidicated that fruit and native shade tree species were the most important on both organic and conventional farms for all the cocoa age groups but more so on organic farms. Organic farms

maintained 14 native tree species facing a conservation issue compared to 10 on conventional cocoa farms. The results suggest that diversified organic cocoa farms can serve as reservoirs of native tree species, including those currently facing conservation concerns thereby providing support and contributing to the conservation of tree species in the landscape.

2.1 Introduction

Cocoa agroforestry is a production system in which farmers intentionally integrate shade trees with cocoa trees on the same plot together with food crops. Since cocoa agroforests are in many ways – e.g. in terms of tree cover, composition and structure – closer to natural forest ecosystems compared to monocultures it is receiving a lot of attention following the realisation of its potential to conserve biodiversity and provide environmental, biological, ecological and socio-economic benefits at various nested scales such as plot, farm, landscape and ecoregion (Norris *et al.*, 2010; FAO, 2011; Mbolo *et al.,* 2016; Rajab *et al.,* 2016). Cocoa agroforests conserve native plant and animal diversity (Saj *et al.,* 2017) and provide co-products which diversify farmers' diets as well as supplementary income and some security from climate change related shocks (Bandanaa *et al.*, 2014; Vaast and Somarriba, 2014; Jacobi *et al.*, 2015). As future climate predictions suggest a reduction of suitable cocoa production areas in both Ghana and Côte d'Ivoire (Gockowski and Sonwa, 2011), the two major cocoa producers, cocoa agroforests may play a significant role in sustaining cocoa production in these countries as these systems have the potential to improve micro-climatic conditions thus enhancing their ecological resilience (Vaast and Somarriba, 2014; Tondoh *et al.*, 2015).

There is a growing global demand for cocoa, and it is estimated that in the next decade world cocoa production and price will rise by

10% and 25% respectively (ICCO, 2014). To meet this demand, farmers' immediate response, as it had been in the past, includes intensification and/or expansion of cocoa production systems, both of which have been cited as drivers of deforestation and declining biodiversity in West Africa and elsewhere (Vaast and Somarriba, 2014; Tondoh *et al.*, 2015; Rajab *et al.,* 2016).

Cocoa is mostly grown under partial cleared forests; the retained trees provide shade for cocoa and co-products for farmers while shade tree leaf litter inputs and accumulated nutrients in forests soil ensure productivity (Tondoh *et al.*, 2015; Wessel and Quist-Wessel, 2015). However, farmers tend to gradually replace native trees with food crops or fruits (e.g. *Citrus spp.* and *Musa spp.*) and plant more cocoa as the cocoa trees mature to increase income (Gockowski and Sonwa, 2011; Asare *et al.*, 2014). This trend of simplification within cocoa agroforests leads to the creation of agrochemical-dependent cocoa systems referred to as conventional cocoa systems, which smallholders cannot manage due to high input costs (Bandanaa *et al.*, 2014; Wessel and Quist-Wessel, 2015). Therefore, cocoa intensification within the current socio-economic context of cocoa farmers may result in shifts in cocoa production to new frontiers through clearance of forests land thus enhancing deforestation. Moreover, use of synthetic agrochemicals in the conventional cocoa systems may negatively modify soil biota composition which could affect soil health that underpins productivity (Barrios *et al.*, 2015).

Organic farming involves production systems with an inherent ethos to sustain the health of soils, ecosystems and people, and prohibits the use of synthetic agrochemicals (Bandanaa *et al.*, 2014; Barrios *et al.*, 2015). Since synthetic agrochemicals such as fertilizer, pesticides and herbicides are not permitted in organic farming, farmers pursue one of two strategies; organic monocultures or organic agroforests. Organic cocoa monocultures rely solely on organic agrochemicals for soil nutrient replenishment and control of weeds, pests and diseases. Organic cocoa agroforests make use of a variety of shade trees to suppress weed growth and insect pest outbreaks (Tscharntke *et al*., 2011; Vanhove *et al.,* 2016), and to compensate for nutrient losses due to nutrient uptake by cocoa trees through nitrogen fixation, reduced nutrient leakage and decomposition of litter from shade trees (Asase *et al*., 2009; Vanhove *et al.,* 2016). Cocoa trees also benefit from microclimate amelioration and increased water retention (Rajab *et al.,* 2016; Vaast and Somarriba, 2014; Tscharntke *et al*., 2011).

Additionally, the shade trees provide a range of benefits to people, soils and ecosystems such as; (i) provision of food and fruits (Jacobi *et al.*, 2015), (ii) enhanced soil and water quality through reduced erosion and pollution (Tscharntke *et al*., 2011), (iii) maintenance of high levels of native species and functional agrobiodiversity (Jacobi *et al.*, 2015), (iv) increased farm resilience (Bandanaa *et al.*, 2014) and carbon sequestration (Vaast and Somarriba, 2014; Jacobi *et al.*, 2015; Rajab *et al.,* 2016; Saj *et al.*, 2017) and its attendant climate change mitigation benefits.

Therefore, organic cocoa farming that makes use of diverse shade trees (agroforestry) might contribute meaningfully to the mitigation of biological diversity loss in the tropics (Bandanaa *et al.,* 2014; Haggar *et al.,* 2015), especially in regions where forest cover has been significantly reduced (Norris *et al.,* 2010). Furthermore, it has been suggested that an integration of organic farming (i.e. the use of solely organic inputs) and agroforestry (introduction of trees on farmlands) would enhance biodiversity conservation (FAO, 2011; Bandanaa *et al.,* 2014; Barrios *et al.*, 2015) and integration has been strongly recommended for Africa (FAO, 2011; Scialabba and Müller-Lindenlauf, 2010). However, robust data supporting this claim are lacking, especially in tropical and developing countries (Niggli *et al.,* 2008; Scialabba and Müller-Lindenlauf, 2010).

In Ghana, the integration of organic farming practices into shade cocoa production (i.e. organic cocoa agroforestry) is not a recent phenomenon, as systems date back to 1870 when cocoa was first introduced but organic certification is a relatively new phenomenon (Bandanaa *et al.,* 2014; Benefoh, 2018). While conventional cocoa production has been carried out using shade systems, and in some cases without shade trees (full sun), fertilisation of cocoa plots and the control of pests and diseases have been undertaken using inorganic inputs. The recruitment of shade tree species in cocoa systems is a reflection of what farmers deem important for the provision of shade and other ecological services (Tscharntke *et al.*, 2011; Asare *et al.*, 2014). Thus, it is essential to understand the importance value – a measure of how dominant a species is in a given ecosystem – of shade tree species in cocoa agroforestry systems. The composition and structure of cocoa agroforestry systems changes with time via management, thus dominant shade tree species at each stage as the cocoa systems mature is closely linked to management (Asare *et al.*, 2014; Asare and Anders, 2016).

There is a consensus that agroforestry systems can conserve flora and fauna better than monocultural crop systems, but not native forests (e.g. Tscharntke *et al.*, 2011; Vaast and Somarriba, 2014; Tondoh *et al.,* 2015; Rajab *et al.*, 2016; Saj *et al.*, 2017). However, little is known about the contribution of organic cocoa agroforests to the conservation of flora and fauna, making it difficult to quantitatively evaluate their contribution to the conservation of floristic diversity but such data is vital for biodiversity conservation because the major cocoa production areas are also classified as biodiversity hotspots (Norris *et al.,* 2010; Scialabba and Müller-Lindenlauf, 2010; FAO, 2011; Tscharntke *et al.*, 2011). Moreover, given the large spatial extent of cocoa systems in the major cocoa production countries (Norris *et al.,* 2010; Gockowski and Sonwa, 2011; Suhum Municipality Report, 2014), the significant overlap with biodiversity hotspots (Norris *et al.,* 2010; FAO, 2011; Tscharntke *et al.*, 2011) and the debate on land-sparing or land-sharing species conservation strategies (Wade *et al.,* 2010; Gockowski and Sonwa, 2011), it is crucial to evaluate the potential of cocoa systems to conserve tree diversity. It has been observed that the adoption of land-sparing and agroecological methods like cocoa agroforestry can create a more biodiversity-friendly agricultural matrix (Tscharntke *et al.*, 2011; Altieri and Nicholls, 2012) to develop complex, multilayered habitats, and improve connectivity thus exhibiting potential for providing a solution to the biodiversity-food trade-off (Kremen, 2015).

There is also a growing consumer demand for organic commodities coupled with advocacy by environmentalists for organic cocoa because such systems tend to be more ecologically sustainable compared with conventional systems (Bandanaa *et al.,* 2014; Haggar *et al.,* 2015; Jacobi *et al.,* 2015). Yet, in West Africa the comparison of shade organic cocoa systems and conventional cocoa systems in terms of biodiversity benefits is not well documented. The present research seeks to bridge these gaps and to contribute to the understanding of the benefits of organic cocoa agroforests in terms of conservation of native shade tree species. Specifically, the study compared the community structure (abundance, heterogeneity, richness and composition) of organic and conventional farms. It also determined the conservation status and importance value of shade species (i.e. both woody and non-woody shade providing plants) in both production systems. Finally, it determined the shade strategies (the stem density/number and type of shade species planted/retained on cocoa farms) utilized by farmers. The study hypothesized that organic cocoa farms will be more diversified in structure and richer in shade species composition compared to conventional farms.

2.2 Methodology

2.2.1 Study area

The study was conducted in seven randomly selected cocoa growing communities (Nsuta, Owawase, Safrosua, Sebiase, Yaw Kwapong, Abeho and Kuano) in the Suhum Municipality in the Eastern Region of Ghana. Suhum lies about 60 km north-north-west of Accra (the capital of Ghana) at N 6^o 5′ and W 0^o 27′ and is about 400 km^2 (Figure 2.1; Hunter, 1963; Suhum Municipality Report, 2014). Cocoa farming in Ghana originated from the Eastern Region (Asare *et al.*, 2014; Asare and Anders, 2016) the part of Ghana where Suhum is located and Suhum harbours the country's oldest organic cocoa farms as it was pioneered in this area.

Ecologically, Suhum lies within the semi-deciduous forest zone but anthropogenic activities such as agriculture, logging and extraction of fuelwood have reduced the original vegetation to an insignificant level and the land is now mainly covered by fallows and secondary forests (Wade *et al.*, 2010). The shaded-cocoa systems in the area are mostly mixed stands of cocoa with variable proportions of naturally generated upper canopy shade trees such as *Terminalia superba* Engl. & Diels, *Entandophragma angolense* (Welw.) C.DC, *Alstonia boonei* de Wild, *Antiaris toxicaria* Lesch. and *Spathodea campanulata* P. Beauv. Increasingly, fruit trees including orange (*Citrus sinensis*) (L.) Osbeck, Avocado (*Persea americana* Mill.) and mango (*Mangifera indica* L.) are planted for shade, food and other purposes. The cocoa farms are generally small-scale in nature typically not exceeding 2 hectares. Cocoa trees are planted at a spacing of 3 m × 3 m giving a planting density of approximately 1100 trees/hectare with majority of farms having the recommended 12 - 18 shade trees per hectare corresponding to 30-40% canopy cover (Asare and Anders, 2016).

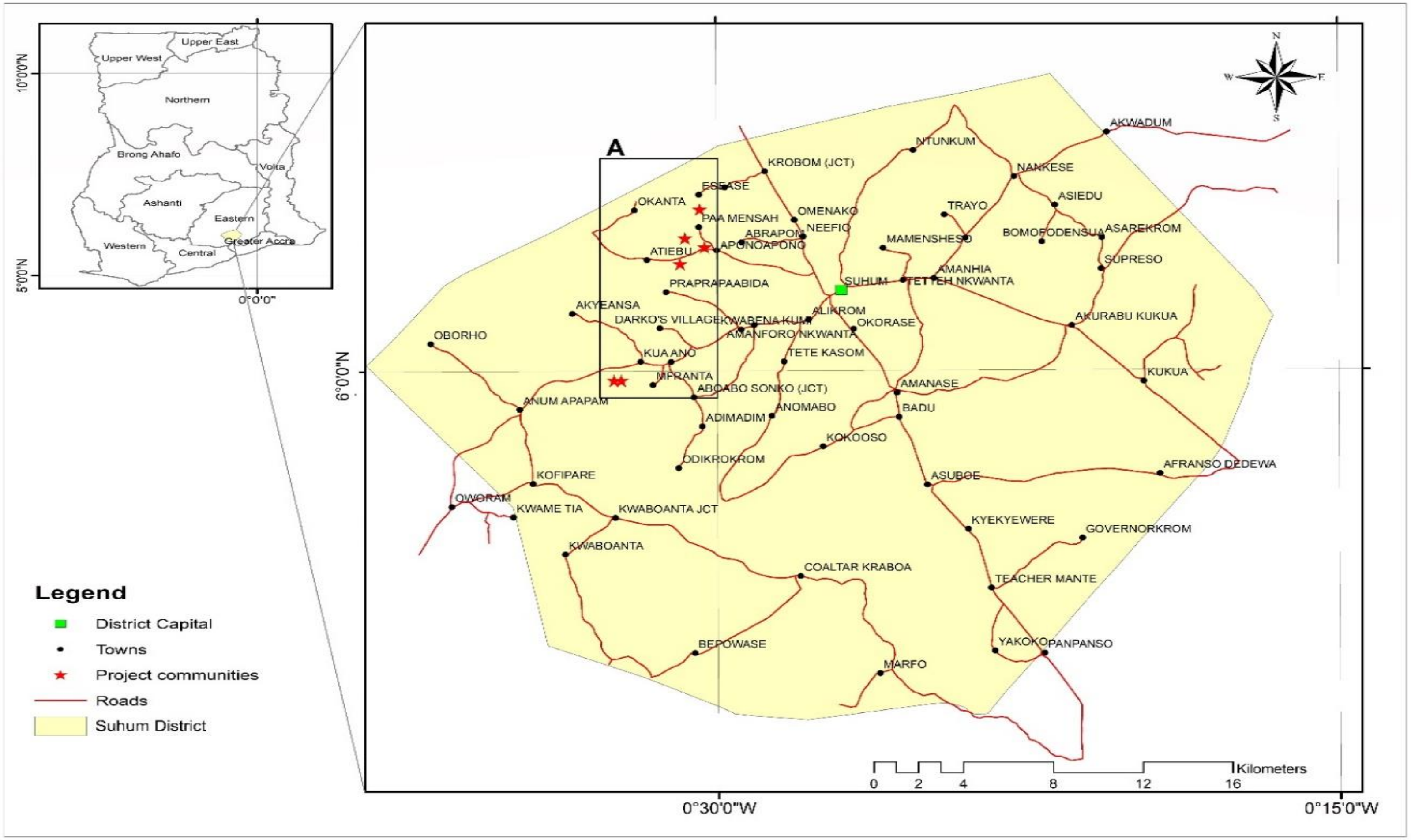

Figure 2.1 Map of study area

The major management practices undertaken are shade control, fertiliser application, weeding, pest and disease control, harvesting of pods and processing of beans. Currently, the Cocoa Research Institute of Ghana recommends the application of specially formulated cocoa fertiliser "Asaase wura" (0-22-18+ 9Ca+7S+6MgO) (African Cocoa Initiative, 2012) at the rate of 7.5 bags (375 kg ha^{-1}) and "Nitrabor" (Nitrogen + boron) at the rate of (2.5 bags) 125 kg ha^{-1}. The cocoa farms in the area are either organically or conventionally managed. Organic farming prohibits the use of synthetic agrochemicals such as inorganic fertilizers, pesticides, herbicides and fungicides and encourages the use of manure, mulch, organic fertilizer and organic pesticides while conventional farming uses synthetic agrochemicals. Both organic and conventional cocoa farmers in the study area maintain shade trees on their cocoa farms. Yields from both systems vary over a wide range ranging from 400-800 kg ha^{-1} (Wade *et al.,* 2010; *Personal com.*).

In this study, organic cocoa farms are defined as cocoa agroforests (shade cocoa) that have been managed for at least five years using only certified organic inputs (i.e. organic fertilizer, organic pesticides and herbicides) to produce cocoa beans that meet international standards for the production of organic cocoa. All the organic cocoa farmers were registered and certified by Control Union; an international certification body active in more than 70 countries (Web 1).

Rainfall in the study area ranges from 1270 mm to 1651 mm and is bimodal, i.e. major season (April to July) and minor season (September to November) with a dry spell or main dry season (November to March). Average temperature ranges from 24^o C to 29^o C, relative humidity for the rainy and dry seasons ranges from 87% - 91% and 48% - 52% respectively (Wade *et al.,* 2010). The municipality is rain fed agrarian, with cocoa farming being the major occupation; other sources of livelihood include cultivation of food crops, poultry, forestry and trading. Soils in the study area were formed from similar thoroughly weathered parent material; they are porous, well drained and loamy and are grouped under forest ochrosols (FAO, 1991; Ministry of Food and Agriculture (MoFA), 2018). The ecology of the study area is similar to what pertains in the major cocoa growing areas in Ghana (Hawthorne and Jongkind, 2006; Dawoe *et al.,* 2016) and is therefore broadly representative.

2.2.2 Selection of cocoa farms

The present study adopted a multi-stage approach in the selection of study communities and farms/farmers. First the Suhum Municipality was prescribed since the production of organic cocoa beans in Ghana was pioneered here and the oldest organic cocoa farms can be found within the Municipality. Next seven cocoa producing communities within the Municipality known to have farmers producing organic cocoa were randomly selected from a list obtained from local offices of the Ghana COCOBOD (regulators of the cocoa sector). Organic and conventional cocoa farmers/farms were then randomly selected from separate lists provided by the regulators. Where a farmer had more than one of a particular farm type, only one was selected randomly. Conventional farms are cocoa agroforest managed using inorganic inputs. Both the organic and conventional cocoa farms were categorised into three cocoa age groups namely; Young Cocoa Systems (YCS, ≤ 15 years), Mature Cocoa Systems (MCS, 16 to 30 years) and Old Cocoa Systems (OCS, ≥ 31 years) and 14 cocoa farms were selected *per* cocoa age group *per* farm type (i.e. overall, 42 organic and 42 conventional farms were selected). Land preparation methods, management practices and cropping history of farms were similar. All the selected sites were neighbouring communities except two which were located 8-10 km away. All selected farmers/landowners agreed to participate in the research and no further permission was required.

2.2.3 Species inventory and quantitative measurement

The area of the farm was obtained by walking along its perimeter with a Global Positioning System (Garmin GPSMAP 62s) after which a 25 m x 25 m plot was then randomly established (Asare *et al.*, 2014; Dawoe *et al.,* 2016). Shade trees and shrubs were identified to the species level (botanical and local names) with the help of an experienced forest technician (from the Council for Scientific and Industrial Research) and two local informants and after Hawthorne and Jongkind (2006). The uses of all the shade species were also determined and recorded. The circumference of the stem of all shade species and cocoa trees (>5 cm) were measured at 1.3

meters above the ground with a tape measure in centimetres and later converted to diameter values. For multi-stemmed plants, each stem was measured, and the equivalent diameter of the plant estimated by taking the square root of the sum of the diameter squared of all stems *per* plant (Snowdon *et al.*, 2002). All data were collected between April and August 2016.

2.2.4 Data processing and estimation of quantitative parameters

2.2.4.1 Shade trees species diversity and richness

Shade trees species richness (hereafter species richness) *per* plot was estimated by counting the number of species in each plot (i.e. observed species richness). The total species richness on organic and conventional farms in each cocoa age-group was calculated using two non-parametric estimators; (i) second-order Jacknife (Burnham and Overton, 1979), which is based on the observed frequency of rare species and minimises the bias of using observed species richness as an estimator and (ii) the singletons and doubletons of Chao (Chao, 1984), which provides a lower bound estimate of species richness. The Chao1 total richness (S_{chao1}) and the second-order Jackknife (S_{jk2}) were calculated as $S_{chao1} = S_o + [a^2/(2b)]$ and $S_{jk2} = S_o + 2a - b$, where S_o is observed species richness, a is the number of singletons and b is the number of doubletons ($b > 0$).

Shannon diversity index (H’), Simpson’s reciprocal index (1/D) and Margalef’s diversity index (Dmg) (Krebs, 2014) were estimated in all sampled plots and used together to provide an assessment of the richness and diversity of the shade trees in the two systems. Shannon diversity index is weighted towards rare species, independent of sample size commonly used in biodiversity surveys and combines both species abundance and richness thus comparison with other studies can be done with ease (Magurran, 2004; Krebs, 2014). The Shannon diversity was calculated as; $H' = -\Sigma pi*(Ln\ pi)$, pi is equal to n_i/N, where n_i is the number of individuals *per* species *i* and N is the total number of individuals *per* study plot thus *pi* is the proportion of individuals in species *i*. The Simpson's reciprocal index gives more importance to species abundance and takes into account both species richness and evenness; it was calculated using the formula $1/D = 1/\Sigma[(n(n-1))/N(N-1)]$, where n is the total count of individuals for a particular species in the sample and N is the total count of individuals in the sample. The Margalef index, which is weighted towards species richness and has no limit value but is sensitive to sample size, was calculated as $D_{mg} = (S-1)/In\ N$, where S is species richness and N is the number of individuals.

2.2.4.2 Spatial structure and composition of cocoa farms

Species composition of the two cocoa production systems in each cocoa age group was assessed *via* Jaccard and Sørensen indices, both of which weight matches and mismatches using species presence/absence data sets (Krebs, 2014). To compare spatial structure, all shade providing species were grouped into trees (trees not maintained for food or fruits e.g. *Milicia excelsa*) and food and fruits (trees/crops maintained for fruits or food e.g. *Citrus spp.* and *Musa spp*). Stem densities and basal areas of all shade providing species – as well as that of cocoa were estimated. In order to assess shade trees/species management by the farmers, all associated trees were grouped into domestic (trees maintained to meet domestic needs e.g. food, medicine, etc), ecological (trees maintained to provide shade, fix nitrogen, etc) and economic (trees maintained for income e.g. timber *spp*.) based on their uses. Canopy cover was estimated after Asare and Andres (2016). In brief, crown diameter was measured in four different directions, from one tip of the crown spread to the other, following the cardinal points. The crown area (CA) of each shade tree was estimated assuming a circular crown and was used as proxy for its canopy cover. The total canopy cover (CC) of all shade trees was expressed as a percentage using the formula:

$$CC = \left(\frac{Total\ canopy\ area}{\text{Plot size}}\right) x\ 100\%$$

2.2.4.3 Shade tree species conservation status and ecological importance

Shade tree species with conservation interest were checked using the IUCN Red List of Threatened Species (IUCN, 2016) and in-country star categories for species with conservation priority (Hawthorne and Abu-Juam, 1995). The IUCN Red List categories include; critically endangered (CR), endangered (EN), vulnerable

(VU) and near threatened (NR), repectively defined as species whose risk of extinction in the wild was imminent, extremely high, high and likely in the future. The in-country star categories include; (i) Black star – species require urgent conservation attention because it is globally rare and nationally uncommon, (ii) Gold star – species needs conservation attention because it is fairly rare worldwide and/or nationally, (iii) Blue star – species needs protection because it is rare nationally and common globally or vice-versa, (iv) Scarlet star – species requires urgent control measures because though the species is nationally common it is facing high exploitation pressure and (v) Red star – species needs some control measures because though the species is nationally common it is facing exploitation pressure (Hawthorne and Abu-Juam, 1995).

The Importance Value Index (IVI) of each species was estimated as IVI = RA+RD+ RF, where RA is relative abundance calculated as the number of individuals *per* species *per* hectare, RD is relative dominance defined as the basal area *per* species *per* hectare and RF is relative frequency (*per* ha) estimated as the proportion of plots in a cocoa production system where the species occurred at least once. The IVI which was developed by Curtis and McIntosh (1951) was used in this study as a proxy for ecological importance of shade species and the composition of dominant species in organic and conventional cocoa systems were assessed by comparing ten species with high IVIs (Mbolo *et al.,* 2016).

2.2.5 Statistical analysis

Data conforming to the assumptions of ANOVA were assessed using residual plots and two-way analysis of variance (ANOVA) was used to assess statistical differences between farm types (Org. vs. Con.) and cocoa age-groups (Young, Mature and Old); Least Significant Difference (LSD) post hoc test was conducted where there was significant difference among cocoa age-groups. A Kruskal-Wallis test (K-W ANOVA) was used where the data were not normally distributed. Where interaction terms were not significant, only main effects were considered in results and discussion. A Chi-Square test was used to establish association between cocoa age-groups or farm type and tree use group in terms of species richness and stem density. All the data were processed and analyzed using GenSat (version 17.1). Differences between assessed indices and variables in the two cocoa production systems were considered significant at $p < 0.05$.

2.3 Results

2.3.1 Shade tree species abundance and importance value

In the YCS, 454 individuals belonging to 41 species and 18 families were found in the organic systems whereas 198 individuals belonging to 36 species and 18 families were recorded in the conventional systems. The organic farms of the MCS recorded 387 individuals, 41 species and 22 families whereas 182 individuals, 35 species and 17 families were documented on the conventional MCS farms. The organic OCS recorded 19 families, 38 species and 299 individuals whereas the conventional OCS had 17 families, 27 species and 114 individuals. All recorded shade trees were native species, except *Cedrela odorata* L.*, Artocarpus altilis* (Parkinson) Fosberg, *Gliricidia sepium* (Jacq.) Walp. and *Leucaena leucocephala* (Lam.) de Wit.

The food and fruit species *Musa sapientum* L. f. thomsonii King ex Baker*, Musa paradisiaca* L.*, Mangifera indica, Carica papaya* L.*, Citrus sinensis* and *Persea americana* were present in all the studied organic farms. Additionally*, Chrysophyllum subnudum* (Bak.) which is an important forest fruit for domestic consumption with potential for local and international markets were found on the mature and old organic farms. *Carica papaya, Musa sapientum, Musa paradisiaca* and *Persea americana* occurred on all the studied conventional farms. *Citrus aurantifolia* (Christm.) Swingle*, Citrus sinensis, Cocos nucifera* L.*, Mangifera indica* and *Psidium guajava* (L.) were found in at least one of the three cocoa age groups. The relative abundance of food and fruit species (*per* ha) ranged from 77.5% to 79.8% on organic farms and 45.4% to 63.8% on conventional farms (Appendix Table 1).

Important timber species such as *Terminalia ivorensis* (A. Chev.) and *Entandrophragma angolense* (Welw.) C.DC. and *Ficus sur* Forssk., a lesser utilized timber species, were also relatively dominant in the organic MCS, whereas *Alstonia boonei* and *Morinda lucida* Benth., both important medicinal plants in West Africa, were relatively dominant in the organic OCS. Forest trees such as *Holarrhena floribunda* (G. Don) Dur and Schinz and *Morinda lucida* were also relatively abundant on the young conventional farms. The relative abundance of nitrogen fixing trees was 6% ha^{-1} on organic farms whilst that of conventional farms was 2.6% ha^{-1}.

IVI values indicated that the ten most abundant shade species represented 71.2%, 71.6% and 70.8% of recorded species in the organic YCS, MCS and OCS respectively and 67.1%, 70.0% and 68.3% of the species found in the conventional YCS, MCS and OCS respectively (Appendix Table 2). The most important species on the organic farms (i.e. YCS, MCS and OCS) were the food and fruit species *Musa spp.*, *Citrus sinensis*, *Persea americana* and *Magnifera indica,* valuable timber species *Terminalia ivorensis, Milicia regia* (A.Chev.) Berg and *Entandrophragma angolense*, and important medicinal species *Alstonia boonei, Morinda lucida* and *Holarrhena floribunda*. Other ecologically and economically important species noted among the ten most important species were *Newbouldia laevis* (P. Beauv.) Seemann ex Bureau*, Spathodea campanulata*, *Sterculia tragacantha* Lindl., *Ficus exasperata* Vahl and *Ficus sur*.

For the conventional farms (i.e. YCS, MCS and OCS), the food and fruit species *Musa spp.*, *Citrus spp., Carica papaya*, *Cocos nucifera* and *Persea americana* were found to be the most abundant. Some valuable timber species such as *Milicia excelsa* (Welw.) C.C.Berg, *Antiaris toxicaria* and *Terminalia ivorensis* were among the ten most important species (Appendix Table 2). Medicinal plants such as

Voacanga africana Stapf, *Morinda lucida*, *Holarrhena floribunda* and forest species *Rauvolfia vomitoria* Afzel, *Lonchocarpus sericeus* (Poir.) Kunth ex DC. and *Ficus exasperata* were notably important on the conventional farms.

2.3.2 Shade tree species richness and diversity

The number of shade tree species *per* plot on the organic farms ranged from 2-13 with an average of 5.10 ± 0.38 and on the conventional farms, a range of 0-13 species with an average of 3.48 ± 0.39 was recorded. The total estimated species richness based on Chao1 and the second-order Jackknife were 111.68 ± 21.53 and 119 respectively for the organic farms and 90.80 ± 17.99 and 99 for the conventional farms in the studied cocoa systems. Organic farms had significantly higher mean species richness ($F_{1, 78} = 8.91$, $p = 0.004$), Shannon diversity index ($F_{1, 78} = 12.80$, $p < 0.001$), Simpson's reciprocal diversity index ($F_{1, 78} = 12.25$, $p < 0.001$) and Margalef diversity index ($F_{1, 78} = 12.22$, $p < 0.001$) when compared to conventional farms (Figure 2.2). Average species richness and diversity indices values were similar across the different cocoa-age groups.

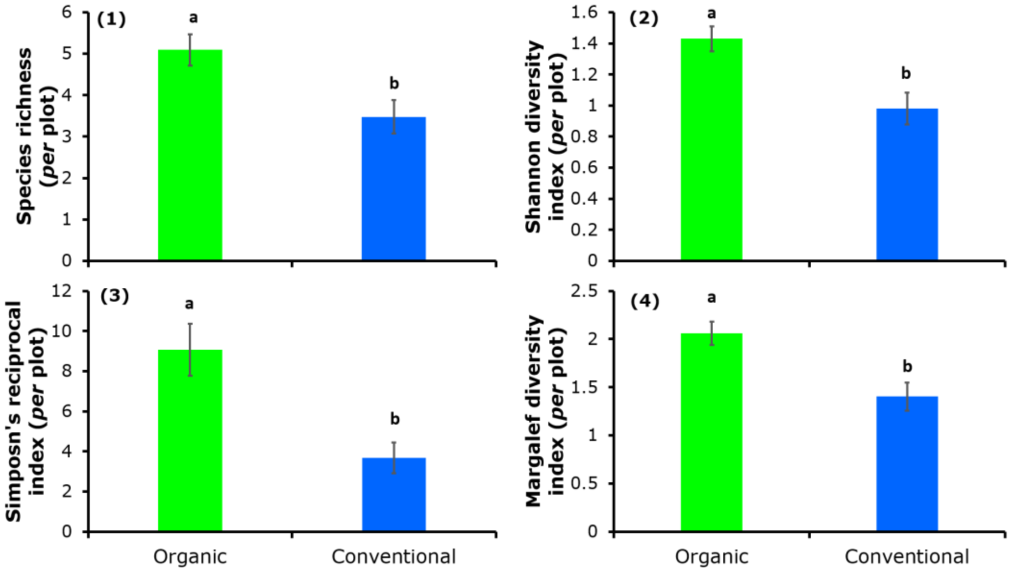

Figure 2.2 Mean shade species richness and diversity indices (per plot ± SEM, n = 42) between organic and conventional cocoa systems at Suhum. Bars of Farm Type (Organic vs. Conventional) with different letters implies significant differences at α = 0.05.

The richest families in the organic YCS were Moraceae (8 *spp.*), Sterculiaceae (5 *spp.*), Fabaceae (4 *spp.*) and Apocynaceae (4 *spp.*) while Moraceae (7 *spp.*), Fabaceae (4 *spp.*) and Apocynaceae (4 *spp.*) were the richest families for the conventional YCS. Few species (i.e. 1-3) were observed for all the other families found on organic and conventional farms. For the MCS, Moraceae and Fabaceae (6 *spp.* each) were the richest families on both the organic and conventional farms; the other documented families recorded ≤ 3 *spp. per* family. However, in the organic OCS, three families Fabaceae (6 *spp.*), Moraceae (5 *spp.*) and Apocynaceae (4 *spp.*) were the richest. In conventional OCS, the richest documented families were Moraceae and Apocynaceae (4 *spp.* each).

2.3.3 Spatial structure and composition of organic and conventional cocoa farms

On organic farms there was a threefold increase in the density of food and fruits shade trees (*per* ha) when compared to conventional farms (Org. 341 ± 38 vs. Con. 106 ± 18) and the mean-ranks of fruit trees density were significantly different between the farm types (H = 29.88, df = 1, $p < 0.001$). Both shade tree density and total density did not differ significantly between organic and conventional farms but the density of cocoa trees (Org. 1012 ± 40 stems ha^{-1} vs. Con. 1203 ± 40 stems ha^{-1}) were significantly different ($F_{1, 78} = 11.67$, $p = 0.001$). The density of shade trees which were timber species was significantly higher on organic farms compared to conventional farms (Org. 68 ± 7 vs. Con 40 ± 7; H = 11.05, df = 1, $p < 0.001$) but that of non-timber species was similar for both farm types. Canopy cover was significantly greater on organic farms than conventional farms (Org. 52.8 ± 4.2 vs. Con 30.1 ± 3.5 %; $F_{1, 78} = 16.99$, $p < 0.001$) but similar across the different cocoa age groups.

In terms of the basal area, the mean shade trees and total basal areas were significantly higher on organic farms than conventional farms (Figure 2.3; Shade trees; $F_{1, 78} = 70.80$, $p < 0.001$, Total basal area; $F_{1, 26} = 49.05$, $p < 0.001$) but the mean cocoa basal areas were similar. Across the different cocoa age-groups, there was a significant difference between the mean values for cocoa basal area ($F_{2, 78} = 11.93$, $p < 0.001$) as well as mean total basal area ($F_{2, 78} = 3.32$, $p = 0.041$); Least Significant Difference (LSD) post hoc test showed that both the mature and old cocoa systems had higher mean cocoa basal area and total basal area compared to the young cocoa farms. Similar mean shade trees basal area was recorded across the cocoa age-groups. Overall, organic farms were larger than conventional farms, 1.71 ± 0.26 and 1.02 ± 0.19 ha, respectively; the Kruskal Wallis mean-ranks of farm size values differed significantly (H = 8.663, df = 1, $p = 0.003$) between organic and conventional types. Species dissimilarity between organic and conventional systems was greatest for both Jaccard and Sørensen dissimilarity indices in the OCS and least in the YCS (Figure 2.4a-b).

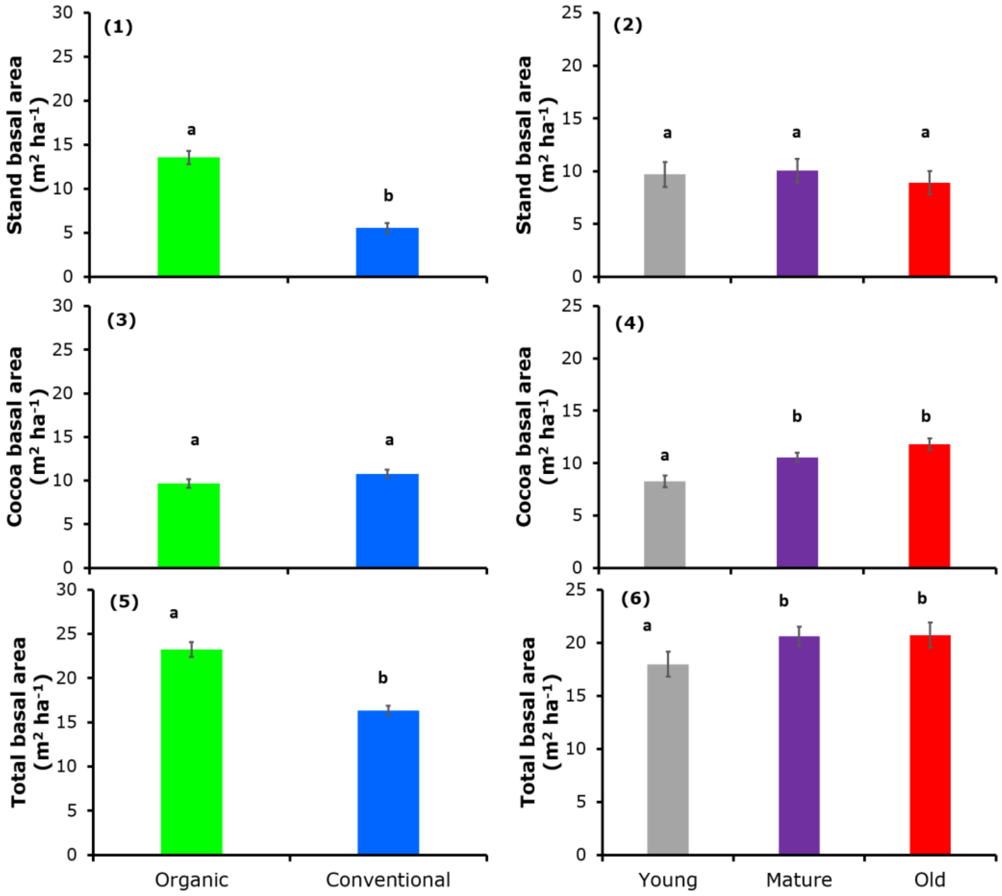

Figure 2.3 Shade stand, cocoa and total basal areas (mean ± SEM) for farm type (n = 42) and cocoa age-groups (young, mature and old, n = 28). Bars of Farm Type or Cocoa Age-group with different letters implies significant differences at α = 0.05.

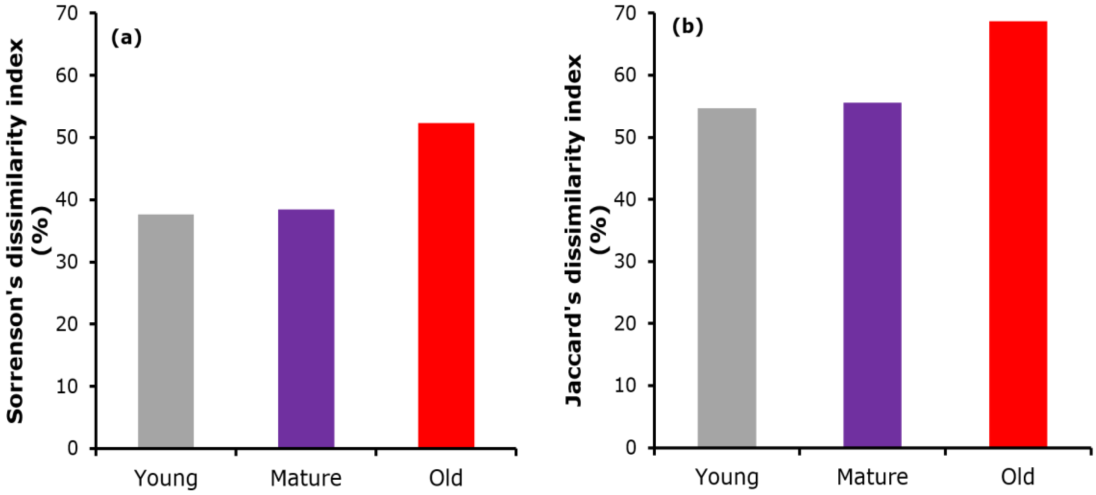

Figure 2.4 Mean species dissimilarity between organic and conventional farms (n = 14) in each cocoa age-group (young, mature and old) at Suhum. ‘a’ is Sørensen’s dissimilarity and ‘b’ is Jaccard’s dissimilarity.

2.3.4 Shade tree species conservation status and ecological importance

Overall, in the organic cocoa systems, a total of 68 species were identified out of which eight species were either endangered, vulnerable or near threatened (Table 2.1). Three of these eight species *Albizia ferruginea, Entandrophragma angolense* and *Pterygota macrocarpa* were only found on organic farms. Three vulnerable species, *Milicia regia Entandrophragma angolense* and *Terminalia ivorensis* were among the ten most ecologically important species on the organic farms. Seven species out of the 57 species recorded in the conventional systems were either endangered, vulnerable or near threatened; two of these seven species *Cedrela odorata* and *Antrocaryon micraster* occurred on only the conventional farms (Table 2.1).

Table 2.1 List of shade species with conservation concern and their relative abundance (R.A), relative dominance (R.D), relative frequency (R.F) and importance value indices (IVIs) at Suhum. The list was generated based on IUCN Red List of Threatened Species and in-country star categories for species with conservation priority.

					Conservation status	
Tree species	**R.A (%)**	**R.D (%)**	**R.F (%)**	**IVIs**	**In-Country**	**IUCN**
Organic cocoa farms						
Albizia ferruginea (Guill. and Perr.) Benth.[a]	0.09	0.13	0.37	0.59	Scarlet	Vulnerable
Albizia glaberrima (Schumach. and Thonn.) Benth.	0.22	0.77	1.04	2.03	Green	Least concern
Ehretia trachyphylla C.H.Wright	0.09	0.04	0.37	0.50	Gold	
Entandrophragma angolense (Welw.) C.DC.[a]	1.40	1.00	4.46	6.87	Red	Vulnerable
Erythrina vogelii Hook f.	0.35	0.25	0.74	1.34	Blue	
Mansonia altissima (A.Chev.) A.Chev.	0.52	0.22	1.09	1.83	Pink	Endangered
Milicia excelsa (Welw.) C.C.Berg	0.09	0.01	0.37	0.47	Scarlet	Near threatened
Milicia regia (Welw.) C.C.Berg	0.96	1.47	2.60	5.04	Scarlet	Vulnerable
Nesogordonia papaverifera (Chev, A.) Cap.	0.35	0.18	1.12	1.65	Pink	Vulnerable
Pterygota macrocarpa K.Schum.[a]	0.09	0.01	0.37	0.47	Red	Vulnerable
Ricinodendron heudelotii (Baill.) Pierre ex Heckel[a]	0.26	0.70	1.12	2.08	Scarlet	
Synsepalum dulcificum (Schum. and Thonn.) Daniell[a]	0.09	0.00	0.37	0.46	Blue	
Terminalia ivorensis A.Chev.	1.67	1.89	3.72	7.28	Scarlet	Vulnerable
Triplochiton scleroxylon K.Schum.[a]	0.09	0.20	0.37	0.66	Scarlet	
Conventional cocoa farms						
Albizia glaberrima (Schumach. and Thonn.) Benth	0.20	0.24	0.55	0.99	Green	Least concern
Antrocaryon micraster A.Chev.[b]	0.20	0.12	0.55	0.88	Red	Vulnerable
Cedrela odorata L.[b]	0.20	0.02	0.55	0.77	Others	Vulnerable
Ehretia trachyphylla C.H.Wright	0.82	0.24	1.64	2.70	Gold	
Erythrina vogelii Hook f.	0.20	0.12	0.55	0.87	Blue	
Mansonia altissima A.Chev.) A.Chev.	0.20	0.08	0.55	0.83	Pink	Endangered
Milicia excelsa (Welw.) C.C.Berg	1.02	0.63	2.19	3.84	Scarlet	Near threatened
Milicia regia (Welw.) C.C.Berg	0.61	0.08	1.09	1.78	Scarlet	Vulnerable
Millettia zechiana Harms[b]	2.66	0.35	2.73	5.74	Green	Least concern
Nesogordonia papaverifera (Chev, A.) Cap.	0.41	1.17	1.09	2.67	Pink	Vulnerable
Terminalia ivorensis A.Chev.	0.82	0.59	2.19	3.60	Scarlet	Vulnerable

a = species found on only organic farms, b = species found on only conventional farms

Star categorisation of species with conservation priority suggests that organic farms recorded a relatively higher number of species for the Blue, Scarlet and Red categories than the conventional farms. Six of the species with in-country species conservation priority occurred on only organic farms, one on only conventional farms and seven on both farm types. Overall, 14 and 10 native tree species with conservation concern were recorded on the organic and conventional farms respectively.

2.3.5 Cocoa shade strategies

In both the organic and conventional systems, the total number of shade species was highest in the YCS and lowest in the OCS (Appendix Table 3). Stem density for economic shade species was highest in the YCS and lowest in the OCS, with the MCS being intermediate. The number and stem density of shade species used for ecological purposes were also highest in YCS and lowest in OCS for the organic systems whereas on the conventional farms, they were highest in the MCS and lowest in the OCS. Shade species used for domestic purposes occurred most in OCS and least in MCS, but their stem density decreased from YCS through the MSC to the OCS.

On the conventional farms, the stem density of domestic species found in the MCS was approximately twice that of the OCS and YCS though it recorded 8 shade species compared to 14 species for YCS and 9 species for OCS. A Chi-square analysis revealed that the number of species in each tree use group was not significantly associated to either farm type or cocoa age group ($p > 0.05$). However, the density of species in each tree use group was significantly associated with both farm type ($\chi^2 = 11.163$, df = 2, $p = 0.004$) and cocoa age group ($\chi^2 = 46.355$, df = 4, $p < 0.001$).

2.4 Discussion

2.4.1 Species abundance and importance value

Generally, the results show that *Musa spp.* and *Citrus spp.* were predominant on both organic and conventional farms for all the cocoa age groups but more so on organic farms. Farmers maintained these food and fruit species in larger numbers due to their economic, domestic and/or ecological benefits (Alemagi *et al.,* 2014; Jacobi *et al.,* 2015). Similarly, Tondoh *et al.* (2015) also reported the dominance of fruit tree species in cocoa systems in Central Western Côte d'Ivoire and indicated that fruits trees were planted by farmers to provide shade and income.

In Ghana, Bandanaa *et al.* (2014) documented 26 flora utilized for food and medicine in a study of cocoa farms in the Ashanti region, and Dawoe *et al.* (2016) reported a relatively higher abundance of non-timber (fruit) trees on cocoa farms in ten districts in the Ashanti, Brong Ahafo and Western regions. The dominance of fruit trees in all these systems could be a strong indication of the deliberate transformation of the landscape by farmers from the naturally occurring pioneer species that have been traditionally grown with cocoa to species that provide food and medicinal benefits.

Apart from *Entandrophragma angolense* which is a non-pioneer light demander and a valuable commercial timber species, all the forest tree species recorded among the ten most abundant species (based on IVI values) on the young, mature and old organic cocoa farms were pioneer species exploited as commercial timber and for use as domestic construction materials (e.g. *Terminalia ivorensis*, *Spathodea campanulata*, *Ficus exasperata, Ficus sur, Alstonia boonei, Milicia regia* and *Sterculia tragacantha*) or medicines (e.g. *Newbouldia laevis, Holarrhena floribunda* and *Morinda lucida*).

Similarly, all the forest tree species of the young, mature and old conventional cocoa farms recorded among the ten most abundant species (based on IVI values) included species with medicinal values namely *Spondias mombin, Rauvolfia vomitoria, Holarrhena floribunda*, *Cola gigantea, Lonchocarpus sericeus, Voacanga Africana, Millettia zechiana* and *Morinda lucida* or domestic construction material and timber species namely *Ficus exasperata*, *Terminalia superba, Antiaris toxicaria, Milicia excelsa, Terminalia ivorensis* and *Spathodea campanulata*. The predominance of similar forest pioneer species on cocoa farms in general has been reported in Ghana (Asase *et al.*, 2009) and in Côte d'Ivoire (Tondoh *et al.*, 2015) and these authors suggested that the observed trend was a result of these species providing commercial and domestic products. Additionally, pioneer species are better able to regenerate and survive in disturbed forests or forest-like systems, such as cocoa agroforests, than other species thus contributing to their abundance on cocoa farms. Indeed, most of the species among the ten most abundant species such as *Milicia excelsa, Antiaris toxicaria, Alstonia boonei, Entandrophragma angolense, Ficus exasperata, Newbouldia laevis, Terminalia ivorensis, Terminalia superba* and *Spathodea campanulata* have been cited as being compatible with cocoa by both farmers and scientists in Ghana (Anim-Kwapong and Osei-Bonsu, 2009; Anglaaere *et al.,* 2011; Asare and Anders, 2016). That notwithstanding, the vegetation in the study area has been cited to be predominantly pioneer species due to significant deforestation that has taken place over the past five decades (Wade *et al.,* 2010; Suhum Municipality Report, 2014). Thus, cocoa agroforestry in the study area affected the presence and abundance of other forest tree species guilds than pioneers.

2.4.2 Shade tree species richness and diversity

In general, the results show that the richest families found on the organic farms were the Sterculiaceae, Moraceae, Fabaceae and Apocynaceae and that of the conventional farms were Moraceae, Fabaceae and Apocynaceae. This observation is a reflection of farmers’ preference for tree species that provide medicine, local construction material and timber or for trees that improve soil fertility in addition to providing shade (Asase *et al.*, 2009; Tscharntke *et al.,* 2011; Asare *et al.*, 2014; Tondoh *et al.,* 2015). For instance, all the species belonging to the family Apocynaceae documented in this study including *Rauvolfia vomitoria, Holarrhena floribunda*, *Voacanga Africana* and *Alstonia boonei* are important sources of domestic or commercial medicinal products. Tree species belonging to the families Sterculiaceae, Moraceae and Fabaceae such as *Albizia ferruginea, Albizia glaberrima, Albizia zygia, Amphimas pterocarpoides, Piptadeniastrum africanum, Gliricidia sepium, Ficus exasperata, Ficus sur, Ficus vogeliana, Antiaris toxicaria, Melicia regia* and *Melicia excelsa* improve soil nutrients through nitrogen fixation, provide quick shade, keeps soil around them cool and moist, or are important sources of both local construction material and commercial timber (Asase *et al.*, 2009; Asare *et al.,* 2014; Dawoe *et al.,* 2016; Anglaaere *et al.,* 2011). Tscharntke *et al.* (2011) asserts that the maintenance of high-value timber trees, such as those documented in the present study, serve as a bank account for cocoa farmers and their families.

Organic cocoa farms were more diverse than the conventional farms in terms of shade tree species, which is a confirmation of the hypothesis of the study. The results of the present study are similar to others conducted elsewhere that investigated coffee (Haggar *et al.,* 2015), cocoa (Jacobi *et al.*, 2015), agriculture (Jastrzebska *et al.*, 2013) and olive groves (Solomou *et al.*, 2013), all of which found significantly higher flora diversity on organic farms compared to conventional farms. Similarly, in the Ashanti region of Ghana, Bandanaa *et al.* (2014) also reported higher species diversity on organic cocoa farms compared to conventional cocoa farms. Several other studies have demonstrated the benefits of high shade tree diversity to cocoa such as suppression of weeds and pests, host for beneficial insects, enrichment of soils and reduction of cocoa physiological stress (Tscharntke *et al.,* 2011; Vanhove *et al.*, 2016); it is obvious organic farmers in the present study sought to exploit these benefits through the introduction or retention of a rich list of shade trees on their farms. In general, the high species richness and diversity on organic farms compared to conventional farms show their potential for tree species conservation. The ecological zone of cocoa in major cocoa production countries significantly overlap with major biodiversity hot spots (Norris *et al.,* 2010; Scialabba and Müller-Lindenlauf, 2010; FAO, 2011; Tscharntke *et al.*, 2011); highly diversified cocoa agroforestry in general and organic cocoa agroforestry in particular may serve as important reservoirs of biodiversity (Bandanaa *et al.,* 2014; Saj *et al.,* 2017).

Tree diversity is an important feature of both resilient farming systems (Jacobi *et al.,* 2015) and climate-smart agriculture (Bandanaa *et al.,* 2014) and organic cocoa agroforests seems promising in this context. Certified organic cocoa enjoys premium price; organic certification as is currently being promoted would be a logical method for incentivizing farmers to adopt cocoa agroforestry and the inclusion of diverse shade trees should be prioritised or at least be encouraged and vigorously promoted as part of the certification procedure. Even though organic cocoa demonstrated greater potential in terms of tree species conservation, larger scale farmer adoption is required to maximise this potential. That notwithstanding, over 50% of the 1.63 million ha of cocoa farms in Ghana do not use agrochemicals and are classified as *de facto* organic (Barrientos *et al.,* 2008; Gockowski *et al,* 2013), thus a huge potential for organic certification already exists.

2.4.3 Spatial structure and composition of organic and conventional farms

Generally, the sizes of studied cocoa farms ranged from 0.70 – 1.80 hectares, which concurs with other studies (Wade *et al.,* 2010; Asare and Anders, 2016). The results reveal that the stem densities of the different tree groups used by farmers as shade for cocoa trees were significantly associated with farm type (organic or conventional) but shade tree and total stem densities were similar on both organic and conventional farms. This suggests that for the same total stem densities, organic and conventional systems make use of different densities of each tree group. For example, organic farms had twice the density of fruit trees as conventional farms which reflects an attempt by organic farmers to increase yields from co-products to supplement their cocoa yield.

The fact that cocoa tree density was significantly greater on conventional farms than the organic farms (Org. 1012 ± 40 stems ha^{-1} vs. Con. 1203 ± 40 stems ha^{-1}) even though both farm types had similar total stem densities implies that the conventional farmers replaced shade and fruit trees with cocoa trees; this is a trade-off farmers often adopt (Saj *et al.,* 2017). The results of shade trees stem density for both organic and conventional farms diverge from those of Asare and Anders (2016) possibly due to regional differences in the structure of cocoa farms (Dawoe *et al.,* 2016) and the exclusion of smaller trees in their study. Shade tree and total basal areas on organic farms were consistently higher than conventional farms due to at least; (i) the retention of large old shade trees; (ii) the planting of fast-growing species; (iii) higher density of timber species; and (iv) abundant fruit trees and plants (Appendix Tables 1 and 3).

The composition of shade species on the organic and conventional farms was dissimilar in each cocoa age group; the highest dissimilarity between organic and conventional farms was observed in the old cocoa age group. The Jaccard dissimilarity results of the present study are contrary to those reported by Bandanaa *et al.* (2014); this is probably because the present study included older organic cocoa farms. At the early stage of organic farming, differences between organic and conventional farms in terms of species composition may be less pronounced because most organic farmers either converted from conventional cocoa systems or established them under similar forests as the conventional ones (personal observation).

2.4.4 Species conservation status and ecological importance

In general, the potential of cocoa agroforests to conserve endemic, native and threatened tree species when compared to monocultures and other land use systems has been shown by several authors (Tscharntke *et al.,* 2011; Asare *et al.,* 2014; Mbolo *et al.,* 2016; Rajab *et al.*, 2016; Saj *et al.*, 2017). The results further deepen this understanding, suggesting that shade organic cocoa may contribute more significantly to native species conservation than conventional farms due to their high shade tree diversity and the maintenance of relatively higher levels of tree species with conservation concern. For example, the number of native tree species with conservation concern which were found on only organic farms was higher compared to conventional farms (Table 2.1). That notwithstanding, as reported in Saj *et al.* (2017), 75% of the documented trees in this study have not yet been assessed to determine their conservation status. The vegetation in the study area has been significantly transformed through deforestation into patches of secondary forests; organic cocoa agroforests may play a key role in the maintenance of native tree species and their gene pool and serve as habitats for species that tolerate some disturbances (Wade *et al.,* 2010; Tscharntke *et al.*, 2011; Bandanaa *et al.,* 2014; Suhum Municipality Report, 2014; Jacobi *et al.,* 2015). In addition to meeting the international standards for the production of organic cocoa, the studied organic cocoa agroforestry farms would also meet the criteria for Bird-Friendly, Rainforest Alliance and Fair-trade as outlined in Philpott *et al.* (2007) for shade-coffee as well as chemical-residue-free UTZ. The incentives from these certification mechanisms may further motivate cocoa farmers to maintain tree biodiverse cocoa systems. However, the benefits from these other certification mechanisms must outweigh any other additional trade-off to make them desirable to cocoa farmers.

Tree pioneer species dominated young, mature and old cocoa farms in both organic and conventional systems (Appendix Table 2). The fact that farmers retained or planted pioneers on their farms reflect the importance of these species for the provision of shade and other ecological services in cocoa agroforestry systems. Pioneers are fast growing which enables rapid establishment, canopy closure and hence provision of shade for cocoa (Hopper *et al.,* 2005; Anglaaere *et al.,* 2011). Additionally, pioneers rapidly produce large standing biomass (Gbètoho *et al.,* 2017), which may enhance ecological services such as carbon sequestration and nutrient recycling (Tondoh *et al.,* 2015; Rajab *et al.*, 2016; Saj *et al.,* 2017). Encouraging the use of pioneer species that are already well adapted to the local ecological conditions maybe a successful approach to ensure, at low cost, the conservation of tree species, particularly pioneers with a conservation concern. Cocoa agroforestry systems are promising in this context. Furthermore, tree pioneer species in cocoa agroforestry systems represent a great opportunity to enhance plant succession as the cocoa systems mature because they can improve site conditions and attract disperser communities (Hopper *et al.,* 2005; Tondoh *et al.,* 2015; Rajab *et al.*, 2016; Gbètoho *et al.,* 2017).

2.4.5 Cocoa shade strategy in studied farms

Although the number of species in each tree use group (ecological, economic and domestic) deployed by farmers was not found to be significantly associated with cocoa age group or farm type, stem density was. This suggests that the management strategy deployed by farmers of the young, mature and old cocoa farms was to manipulate the densities of a similar range of ecological, economic and domestic species to meet their own needs and that of their cocoa (Anglaaere *et al.,* 2011; Tondoh *et al.,* 2015; Saj *et al.,* 2017). On the basis of stem density, it appears both organic and conventional farm types adopted a cocoa shade strategy that provided additional benefits but to different degrees in each cocoa age group. For example, organic farms retained relatively higher stem densities of economic shade trees than conventional farms in each cocoa age group possibly for the purpose of generating additional income.

2.5 Conclusion

The results demonstrate that the studied organic cocoa agroforests maintain higher tree species richness, diversity and basal area compared to the conventional cocoa agroforests although both farm types had similar shade tree stem density. The most abundant forests species were predominantly pioneers with potential to provide medicinal products, timber or local construction material in addition to cocoa shade provision. The richest families on both organic and conventional farms were Moraceae, Fabaceae and Apocynaceae and fewer species (≤ 3 *spp.*) represented all the other documented families. Fruits in general and *Musa spp.* in particular dominated both organic and conventional farms but were higher in the former than the latter. The composition of shade species on the organic and conventional farms was dissimilar in each cocoa age group, with the highest dissimilarity between organic and conventional farms recorded in the old cocoa age group.

The results indicate that organic farms retain species with conservation concern, sometimes in relatively abundant proportions, than conventional cocoa farms thus these may arguably provide some assistance in the conservation of tree species in the landscape. That notwithstanding, a large proportion of the documented trees have not yet been assessed to determine their conservation status. Farmers manipulate the densities of a range of species to meet their own needs and that of their cocoa thus they tend to use shade tree species that provides additional income. The manipulation of shade trees density which does not compromise native tree diversity as the cocoa trees age should be encouraged. The findings emphasize the potential of organic cocoa agroforests to conserve native species. However, inclusion of diverse shade trees should be required or at least encouraged in cocoa farms to realize this potential.

3 BIOMASS AND CARBON STOCKS OF ORGANIC AND CONVENTIONAL COCOA AGROFORESTS, GHANA

Abstract

Cocoa is an important agricultural commodity in the global economy, but its cultivation has been linked to deforestation in Africa, Asia and Latin America. Cocoa agroforestry systems have been credited for storing significant stocks of carbon, thereby contributing to climate change mitigation but the impact of organic management on this potential is unclear, especially in Africa. The present study quantified cocoa and shade trees biomass as well as above- and below-ground and soil carbon stocks of 42 organic and 42 conventional cocoa agroforestry systems in Ghana across three cocoa-age groups; young (≤ 15 years), mature (16-30 years) and old (≥ 31). The carbon stocks data was used to estimate the monetary value of the stored carbon in the two systems. Mean aboveground (Org. 39.6 ± 3.63 vs. Con. 22.1 ± 2.61 Mg C ha^{-1}), belowground (Org. 10.3 ± 0.67 vs. Con. 7.1 ± 0.65 Mg C ha^{-1}) and soil carbon stocks (Org. 59.7 ± 3.36 vs. Con. 49.7 ± 3.33 Mg C ha^{-1}) were greater on organic farms than conventional farms. The overall mean carbon stocks (vegetation and soils) for cocoa farms under organic management was 108.65 Mg C ha^{-1} compared to 76.30 Mg C ha^{-1} for cocoa farms under conventional management. The mean concentration of carbon in litter from organic farms (38.6 %) was greater than conventional farms (35.5 %). The estimated monetary value of the rate of CO_2 equivalent of stored carbon by organic cocoa systems ranged from 74.58 US$ ha^{-1} yr^{-1} in old farms to 208.07 US$ ha^{-1} yr^{-1} in young farms compared to a range of

39.08 US$ ha^{-1} yr^{-1} in old farms to 99.60 US$ ha^{-1} yr^{-1} in young farms on conventional cocoa farms. The results show that organic cocoa agroforestry systems hold a greater potential to accumulate carbon and in addition benefit from carbon schemes than conventional cocoa agroforestry systems. It is concluded that organic management is a crucial tool to capture and store carbon in smallholder cocoa agroforestry systems.

3.1 Introduction

The role of different land use systems in climate change mitigation has been explored by several authors (e.g. Wade *et al.,* 2010; Rajab *et al.*, 2016; Saj *et al.*, 2017; Noumi *et al.*, 2018). Cocoa is an important agricultural commodity in the global economy as it provides livelihoods for 40-50 million people worldwide (Hütz-Adams *et. al*., 2016). The production of cocoa is primarily carried out by 5-6 million smallholder farmers, each cultivating on average 2-3 ha of cocoa per farm and producing 90% of the world's cocoa (European Commission, 2013; Kroeger *et al.,* 2017). Cocoa cultivation can contribute to carbon emission or storage depending on the mode of production (Asase and Tetteh, 2016; Noumi *et al.*, 2018). Furthermore, cocoa expansion and intensification have been linked to loss of forest cover in Africa, Asia and Latin America (Norris *et al.,* 2010; Wade *et al.,* 2010; Gockowski and Sonwa, 2011; Tondoh *et al.*, 2015; Wessel and Quist-Wessel, 2015).

Globally, it is estimated that cocoa expansion replaced 2-3 million ha of forests from 1988-2008 (Gockowski and Sonwa, 2011; Kroeger *et al.,* 2017) and cumulatively 14-15 million ha over the past 50 years (Clough *et al.*, 2009; Vaast and Somarriba, 2014). In Ghana, 80% of total deforestation is driven by agricultural expansion with cocoa production being the largest contributor, accounting for 27% of total deforestation for the period 1990-2008 (European Commission, 2013; Kroeger *et al.,* 2017). Over time, cocoa intensification transforms traditional cocoa systems into simplified systems with a single shade species or no shade resulting in reduced ecological resilience and impaired ability on the part of smallholders to adapt to climate variability (Gockowski and Sonwa, 2011; Vaast and Somarriba, 2014; Tondoh *et al.*, 2015).

Cocoa agroforestry is the practice of farming cocoa with shade trees and other useful plants such as food crops, a traditional mode of cultivating cocoa (Somarriba *et al.*, 2013; Rajab *et al.*, 2016). One way to create carbon-sequestering cocoa systems is to encourage inclusion of trees on cocoa farms. Compelling evidence credits cocoa agroforestry systems for capturing and storing significant amounts of carbon compared to no-shade cocoa systems or other agricultural systems (Schroth *et al.*, 2015; Asase and Tetteh, 2016; Rajab *et al.,* 2016; Noumi *et al.*, 2018). The current average cocoa yield in Ghana is 400 kg ha^{-1} yr^{-1} (Hütz-Adams *et. al*., 2016) and Wade *et al.* (2010) found that at this yield threshold, optimal carbon storage can be attained in cocoa farms if farmers pursued a wildlife-friendly or land-sharing strategy. In Sulawesi, Indonesia, Rajab *et al.* (2016) have reported a fivefold increase in total carbon stocks in tree biodiverse cocoa systems compared to cocoa monocultures without yield losses.

Carbon storage in cocoa systems is accomplished by various pools namely soil, tree biomass, litter, cocoa husks, coarse and fine roots, stumps and deadwood (Norgrove *et al.,* 2013; Schroth *et al.*, 2015; Saj *et al.*, 2017). Several studies have credited shade trees as the major carbon storage pool in cocoa systems, stocking 75 - 90% of total carbon stocks in vegetation (e.g. Oke and Olatiilu, 2011; Norgrove *et al.,* 2013; Rajab 2016; Saj *et al.,* 2017). The potential of an agroforestry system to store optimal levels of carbon often depends on its tree density and age (Schroth *et al.*, 2015; Rajab *et al.*, 2016; Schroth *et al.*, 2016; Saj *et al.*, 2017; Silatsa *et al.*, 2017), but its species composition may also be a key factor. Moreover, the contribution of dominant tree species to carbon capture and storage is unclear. Shade levels in cocoa farms is a reflection of social, economic and ecological factors (Wade *et al.,* 2010; Oke and Olatiilu, 2011) hence there is no consensus on optimal shade levels, but various recommendations exist. The Sustainable Agriculture Network (SAN) (2014) recommends 70 emergent shade tree species *per* ha, which must include a minimum of 12 native species, estimated to provide 40% shade cover but in Ghana, 12-18 emergent shade trees *per* ha amounting to 30-40% shade cover is recommended (Asare and Anders, 2016; Dawoe *et al.,* 2016).

On a global scale, soil stores two to three times the amount of carbon stored in vegetation (Gattinger *et al.,* 2012; Mohammed *et al.,* 2016). Hence 90% of the mitigation potential of the agricultural sector is in its soil (Gattinger *et al.,* 2012). The greatest amount of soil organic carbon is stored within 0-30 cm depth coinciding with the depth to which 80-85% mat of lateral roots of cocoa exist (Wood, 2008). Soil organic carbon storage depends on depth, management system and region (Asase and Tetteh, 2016;

Mohammed *et al.,* 2016); the quantity and quality of litter inputs may potentially affect soil carbon storage. Although cocoa agroforestry systems have been credited for storing significant stocks of carbon (Somarriba *et al.*, 2013; Rajab *et al.*, 2016; Saj *et al.*, 2017; Silatsa *et al.*, 2017), the impact of organic management on this potential is poorly understood. Organic farming is known to have positive impacts on soils and ecosystems (Bandanaa *et al.,* 2014; Jacobi *et al.*, 2015; Blanco-Canqui *et al*., 2017) but its impact on soil organic carbon and nutrient stocks are unclear in West African shaded cocoa systems. In general, studies that compared soil organic carbon storage on organic farms to conventional farms are non-conclusive or unavailable for Africa (Gattinger *et al.,* 2012). A few meta-analyses that found higher soil organic carbon stocks in organic farms than conventional farms exist but with major drawbacks such as being narrative (Scialabba and Müller-Lindenlauf, 2010), use of limited datasets (Mondelaers *et al.,* 2009) or excluded organic agroforestry systems and Africa (Gattinger *et al.,* 2012). Despite the existing data gap, organic farming is generally claimed to provide more soil ecosystem services including carbon sequestration than conventional farming (Scialabba and Müller-Lindenlauf, 2010; Gattinger *et al.,* 2012). Increased soil organic carbon would enhance soil fertility and productivity, improve soil properties and processes and maintain soil biodiversity (Blanco-Canqui *et al*., 2017). Thus, organic farming is not a single mitigation strategy because in addition to carbon sequestration, it potentially offers a range of co-benefits such as biodiversity and soil conservation, and the enhancement of climate change adaptation and rural livelihoods (Gattinger *et al.,* 2012; Muller *et al.,* 2012). Diversified shade organic cocoa systems are increasingly viewed as climate-smart agriculture (Bandanaa *et al.,* 2014) and resilient farming (Jacobi *et al.*, 2015); these systems may also be beneficial for carbon sequestration.

In Ghana, the cocoa sector has been included in the nation's carbon accounting budget. To develop a national carbon accounting strategy in line with its Readiness Plan Proposal requires robust data on carbon storage in cocoa systems. Some evidence has been provided for cocoa systems in general (e.g. Dawoe *et al.,* 2016; Mohammed *et al.*, 2016) but none exist for organic cocoa agroforestry systems. Ghana's definition of a forest under the REDD+ readiness efforts is a minimum of 1 ha with trees taller than 5 m having a canopy cover of at least 15% (Dawoe *at al.,* 2016). That is, organic cocoa systems may also qualify for incentives through the REDD+ (Reduced Emissions from Deforestation and Forest Degradation) or related mechanisms that will provide additional income to farmers. The inclusion of cocoa systems in general and organic cocoa systems in particular in REDD+ intervention activities requires sufficient evidence which is currently generally lacking. To contribute to bridging the existing gaps, this study quantified the total biomass and carbon stocks in vegetation and soils under organic and conventional management in different cocoa temporal stages. It was hypothesised that (i) organic management of cocoa agroforestry systems would lead to greater vegetation and soil carbon stocks than conventional management, and (ii) that organic farming has a greater potential to provide additional income to smallholder producers under REDD+ schemes. Results from this investigation would contribute baseline data on carbon sequestration in cocoa systems under organic and conventional management, which might influence REDD+ strategies in Ghana.

3.2 Methods

3.2.1 Selection of cocoa farms

The present study was conducted in the same study area and plots described in Chapter 2 (Page 27-34). A multi-stage approach was used to select the study communities and farmers; Suhum was purposively selected, seven communities where organic cocoa is produced were randomly selected from a list provided by local offices of the Ghana COCOBOD and organic and conventional cocoa farmers were randomly selected from separate lists provided by the regulators. Selected farms were grouped into three cocoa temporal stages; Young Cocoa (YC, ≤ 15 years), Mature Cocoa (MC, 16-30 years) and Old Cocoa (OC, ≥ 31 years). Fourteen (14) cocoa farms *per* farm type *per* cocoa-age group were selected for the study (overall, 42 organic and 42 conventional). Soil data was collected from eight farms *per* farm type *per* cocoa temporal stage (overall, 24 organic and 24 conventional farms). Farmers who were selected agreed to participate in the research.

3.2.2 Biomass and soil data collection

The circumference of shade species (>15 cm) and cocoa trees were measured at 1.3 m above the forest floor and later converted into diameter values (Dawoe *et al.*, 2016). Using a hypsometer (Haglöf Vertex IV and Transponder), the height of all shade species were measured and recorded. Surface litter was collected by randomly throwing a 50 cm x 50 cm wooden quadrat five times (e.g. Soto-Pinto and Aguirre-Dávila, 2015). Five soil samples *per* depth (0-15 cm and 15-30 cm) *per* plot were collected using a soil auger, composited for each layer after being thoroughly mixed and subsampled for chemical analysis. A 139 cm^3 bulk density cylinder was used to collect two samples *per* plot for bulk density estimation (Jacobi *et al.*, 2015). Cocoa pod husks (three *per* plot) were collected from each farm, oven dried, milled and analysed for carbon content.

3.2.3 Data processing and chemical analysis

The important value indices (IVI) of shade tree species were estimated as described in Chapter 1 (Section 2.2.4.3, Page 39-40). The biomass of shade trees, *Musa spp*., *Citrus spp.* and cocoa were estimated using species-specific or general allometric equations developed from similar ecological areas (Table 3.1). Species-specific wood densities were obtained from the World Agroforestry Centre’s Wood Density Database and Global Wood Density Database (Chave *et al*., 2009; Zanne *et al*., 2009). If a species was not listed, the average for species belonging to its genus in the plot was used and if its genus was not represented by any other species, the average wood density of the plot was used for the unknown species (e.g. Dawoe *et al*., 2016; Rajab *et al*., 2016). Carbon stocks were calculated by multiplying the shade tree or cocoa tree biomass by 0.5 (IPPC, 2006). Collected litter samples were composited for each plot, oven dried at 68° C for 48 hrs, sub-sampled, milled using an agate ball mill at 290 rpm for 15 minutes (e.g. Rajab *et al.*, 2016). Soil samples were oven-dried at 105° C for 48 hrs, sieved using 2 mm sieve, milled using agate ball mill at 200 rpm for 10 minutes (e.g. Jacobi *et al.*, 2015; Mohammed *et al.*, 2016). Milled samples (soil, litter and cocoa pod husks) were analysed for carbon contents using CN analyser (Thermo Scientific™ Flash™ 2000 Organic Elemental Analyzer (OEA)) (Rajab *et al.,* 2016).

Soil bulk density samples were oven-dried in trays of known weight (W_1) at 105° C for 48 hrs, weighed (W_2) and the bulk density (BD) determined as: $BD\ (g\ cm^{-3}) = [(W_1 - W_2)/V] \times (100 - \%CF)/100$, where CF is coarse soil fraction. Soil particle size distribution was assessed via laser ablation (Bechman Coulter LS 200). For this, organic matter was chemically removed by adding 25 ml H_2O_2 to 0.5 g of sieved (<2 mm) air-dried soil samples, placed in water bath at 60° C for 1.5 hrs and then at 90° C for 1.5 hrs. The samples were topped up with 25 ml of deionised water, centrifuged at 3500 rpm for four minutes, decanted and the step repeated with 35 ml of deionized water. Before analysing with laser ablation, 25 ml of

Calgon (7 g sodium carbonate plus 35 g of sodium hexametaphosphate in 1 L of deionized water) was added and well shaken. Soil textural classes were assigned using the USDA soil triangle (Soil Survey Division Staff, 1993).

Table 3.1 List of allometric equations for biomass calculations

Category	**Formula**	**R^2**	**Source**
Shade trees	$AGB = 0.0673*(p*DBH^2*H)$		Chave *et al.,* (2014)
Palm trees	$AGB = 10.0 + 6.4 * H$	0.96	Brown (1997)
Theobroma cacao	$AGB = 10^{(-1.625 + 2.63 * log(DBH))}$	0.98	Andrade *et al.* (2008)
Musaceae	$AGB = 0.0303 * DBH^{2.1345}$	0.99	Pearson *et al.* (2005)
Citrus spp.	$AGB = -6.64 + 0.279*(DBH*DBH*0.3142) + (0.000514 * (DBH*DBH*0.3142)^2))$	0.94	Schroth *et al.* (2002)
Coarse roots	$Y = \exp^{(-1.085 + 0.926 * ln(AGD))}$		Cairns *et al.* (1997)
Soil organic C	$SOC = \%C*BD*Z$		Mohammed *et al.* (2016)

AGB aboveground biomass in kg dry matter, p wood density in g cm^{-3}, DBH diameter at breast height in cm, H height in m, Y coarse root biomass density in Mg ha^{-1}, ABD aboveground biomass density in Mg ha^{-1}, BD is soil bulk density in g cm^{-3}, Z is soil depth in cm, and C is carbon content (%).

3.2.4 Data analysis

Carbon stocks in each plot were fractioned into shade species, cocoa trees, shade trees coarse roots, cocoa trees coarse roots, litter and soil. Aboveground carbon stocks were calculated as the sum of carbon stocks in shade species, cocoa and litter; belowground carbon stocks as the sum of carbon stocks in the coarse roots of shade trees and cocoa; and soil organic carbon was quantified by summing the carbon stocks of both depths (0-15 cm and 15-30 cm). Soil organic carbon was estimated after Mohammed *et al.* (2016) (Table 3.1). Total carbon stocks were estimated as the sum of aboveground, belowground and soil organic carbon stocks. The top 15 shade tree species with high IVIs and their contribution to vegetation carbon stocks were compared for both farms.

The gross monetary value (MV) of total carbon stocks was estimated as MV = P x CE, where CE is the CO_2 equivalent of carbon stocks (CE = carbon stocks x 3.64) and P is the unit price (US $) of CE (Somarriba *et al.,* 2013). The present study used a unit price of US$ 5 in the voluntary markets as reported for Africa (Hamrick and Gallant, 2017). The age of the farms provided by the farmers was used as an estimate for the age of each cocoa system (A) and the gross monetary value of the carbon accumulation rate (i.e. the rate of CE) was calculated as MV/A, assuming linear increment (Somarriba *et al.,* 2013). For each variable, normality of dataset was tested using the Shapiro-Wilks W-test for homogeneity of variances; variables with variances that were not normally distributed were log (base 10) transformed. A two-way analysis of variance (ANOVA) was then used to establish statistical differences; where applicable, this was followed by least significant difference (LSD) post hoc test. Where interaction terms were not significant, only main effects are considered in results and discussion. Differences between variables in the two cocoa production systems were considered significant at $p < 0.05$.

3.3 Results

3.3.1 Aboveground and belowground carbon stocks

The mean concentration of carbon for litter from farms under organic management was significantly higher than those under conventional management (Org. 38 ± 0.41 % vs. Con. 35 ± 0.66 %; $F_{1, 30} = 18.64$, $p < 0.001$). Biomass carbon stocks in aboveground (Org 39.6 ± 3.6 vs. Con 22.1 ± 2.6 Mg C ha^{-1}) and belowground (Org 10.3 ± 0.7 vs. Con 7.1 ± 0.7 Mg C ha^{-1}) were 79 and 45 % higher on organic farms than conventional farms (Aboveground, $F_{1, 78} = 26.19$, $p < 0.001$; Belowground, $F_{1, 78} = 19.25$, $p < 0.001$). The biomass and carbon stocks of shade species were 2.4-fold and 2.2-fold higher on organic farms compared to conventional farms (Figure 3.1a-b; Biomass, $F_{1, 78} = 34.28$, $p < 0.001$; Carbon stocks, $F_{1, 78} = 35.0$, $p < 0.001$). Equally, the amount of biomass and carbon accumulated by the coarse roots of shade trees were 1.7-fold and 1.5-fold respectively higher on organic farms compared to conventional farms (Biomass, $F_{1, 78} = 27.11$, $p < 0.001$; Carbon stocks, $F_{1, 78} = 26.2$, $p < 0.001$). The contribution of shade species and cocoa trees to aboveground biomass carbon were, respectively, 81 and 19% on organic farms, and 63 and 37% on conventional farms. The amount of biomass carbon accumulated in cocoa trees, coarse roots of cocoa trees and litter were similar on both organic and conventional cocoa farms.

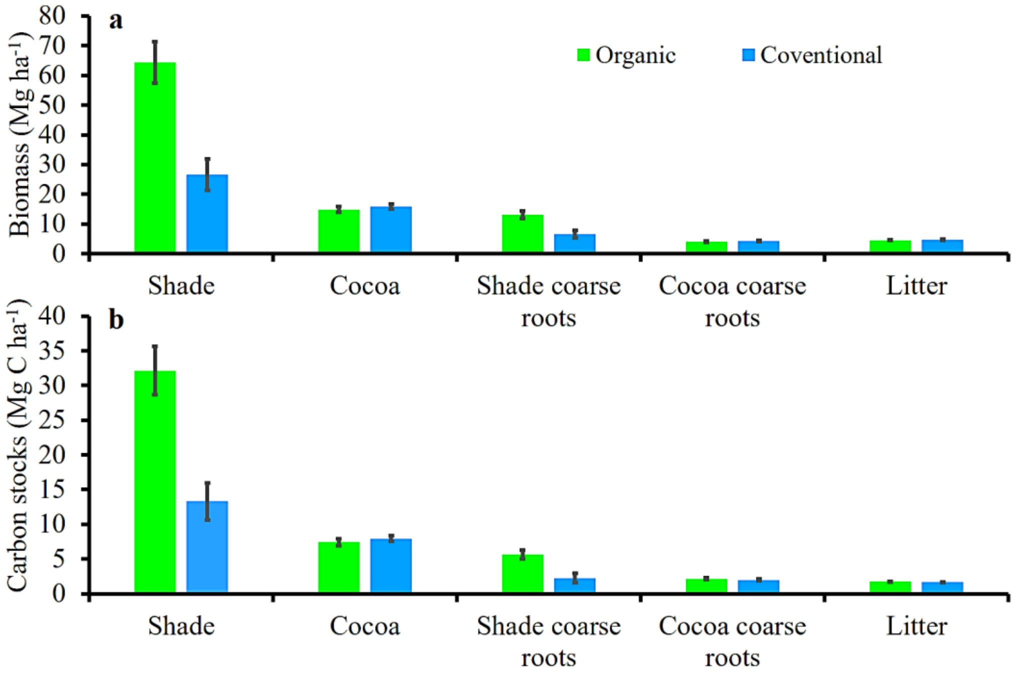

Figure 3.1 Biomass (a) and carbon stocks (b) (Mean± SEM) on organic and conventional farms at Suhum.

In terms of shade tree species contribution to overall vegetation carbon stocks, the top 15 shade tree species stored more than 70 % of the overall vegetation carbon stocks on both organic and conventional cocoa farms (Table 3.2). On organic farms, the shade species that contributed highly to vegetation carbon stocks were also the most important shade species based on the IVIs, except *Aningeria robusta* and *Chrysophyllum subnudum*. Similarly, on conventional cocoa farms, the most important shade species based on the IVIs were also the shade species which contributed highly to vegetation carbon stocks, except *Nesogordonia papaverifera, Cola gigantea, Terminalia ivorensis* and *Cocos nucifera*.

Table 3.2: List of the top 15 shade tree species with high contribution to vegetation carbon stocks and their relative abundance (R.A), relative dominance (R.D), relative frequency (R.F) and importance value indices (IVIs) at Suhum.

Family	**Scientific *name***	**R.A (%)**	**R.D (%)**	**R.F. (%)**	**IVI**	**C Stocks (%)**
Organic farms						
Combretaceae	*Terminalia ivorensis* A. Chev.	6.21	8.20	4.63	19.04	10.99
Moraceae	*Milicia regia* (A.Chev.) C.C.Berg.	3.59	6.37	3.24	13.20	10.15
Anacardiaceae	*Magnifera indica* L.	3.27	9.06	4.17	16.49	8.83
Apocynaceae	*Alstonia boonei* De Wild.	4.90	8.15	4.17	17.22	5.45
Moraceae	*Ficus sur* Forssk.	3.59	6.20	4.17	13.96	4.93
Musaceae	*Musa sapientum* L. f. thomsonii King ex Baker	-	-	-	-	4.27
Meliaceae	*Entandrophragma angolense* (Welw.) C.DC.	5.23	4.35	5.56	15.13	4.04
Rubiaceae	*Morinda lucida* Benth.	6.54	5.12	5.09	16.74	3.82
Bignoniaceae	*Spathodea campanulata* P. Beauv.	1.31	4.45	1.85	7.61	3.45
Sapotaceae	*Aningeria robusta*	0.33	1.74	0.46	2.53	2.61
Rutaceae	*Citrus senensis* (L.) Osbeck	10.13	3.06	6.02	19.21	2.52
Lauraceae	*Pearsea americana* Mill.	4.58	3.51	5.56	13.64	2.39
Sapotaceae	*Chrysophyllum subnudum* (Bak.)	0.98	2.02	1.39	4.39	2.33
Sterculiaceae	*Sterculia tragacantha* Lindl.	1.96	2.18	1.85	5.99	2.30
Bignoniaceae	*Newbondia laevis* (P. Beauv.) Seemann ex Bureau	3.92	1.97	4.17	10.06	2.19
Proportion of total		56.54	66.36	52.31	58.40	70%
Conventional farms						
Fabaceae	*Lonchocarpus sericeus* (Poir.) Kunth ex DC.	1.19	8.77	1.34	11.31	20.92
Apocynaceae	*Holarrhena floribunda* (G. Don) Dur and Schinz	13.89	8.72	9.40	32.00	9.58
Sterculiaceae	*Nesogordonia papaverifera* (Chev, A.) Cap.	0.79	3.91	1.34	6.05	7.21
Rubiaceae	*Morinda lucida* Benth.	9.92	6.30	6.04	22.26	5.79
Sterculiaceae	*Cola gigantea* A Chev.	0.79	4.18	0.67	5.64	5.26
Moraceae	*Antiaris toxicaria* Lesch.	2.78	4.59	3.36	10.72	4.95
Lauraceae	*Persea americana* Mill.	3.97	3.02	3.36	10.35	2.94
Rutaceae	*Citrus sinensis*	4.37	4.19	2.01	10.57	2.90
Apocynaceae	*Voacanga africana* Stapf	9.92	4.50	8.05	22.47	2.86
Rutaceae	*Citrus aurantifolia*	1.59	3.85	2.01	7.45	2.71
Bignoniaceae	*Spathodea campanulata* P. Beauv.	2.78	12.67	2.01	17.46	2.46
Moraceae	*Milicia excelsa* (Welw.) C.C.Berg	1.98	2.10	2.68	6.77	2.36
Moraceae	*Ficus exasperata* Vahl	3.57	3.71	5.37	12.65	2.30
Combretaceae	*Terminalia ivorensis* (A. Chev.)	1.59	1.99	2.68	6.26	2.22
Arecaceae	*Cocos nucifera* (L.)	1.98	2.51	2.01	6.51	2.10
Proportion of total		61.11	75.01	52.35	62.82	77%

3.3.2 Biomass, vegetation carbon stocks and cocoa-age groups

Cocoa tree carbon stocks varied across the cocoa age-groups (Figure 3.2; $F_{1, 78} = 15.71$, $p < 0.001$); Least Significant Difference (LSD) post hoc test showed that cocoa tree carbon stocks decreased in the order Old cocoa > Mature cocoa > Young cocoa. Similarly, carbon stocks accumulated in the coarse roots of cocoa differed significantly across the cocoa-age groups ($F_{1, 78} = 14.86$, $p < 0.001$); LSD post hoc test showed that both the mature and old cocoa farms had higher cocoa tree carbon stocks than the young cocoa farms but average carbon stocks in cocoa coarse roots were similar in the mature and old farms. Shade trees stored 73, 72 and 67 % of vegetation carbon in young, mature and old cocoa farms, respectively. The biomass and carbon stocks of litter, shade trees and shade tree coarse roots were similar across the cocoa-age groups

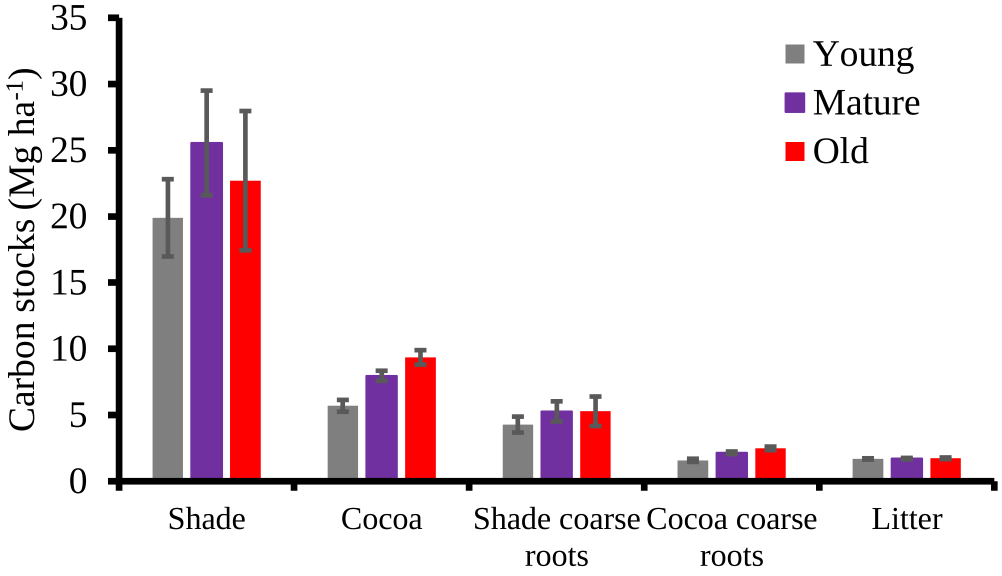

Figure 3.2 Distribution of mean carbon stocks (± SEM) in various fractions across different cocoa-age groups at Suhum.

3.3.3 Soil properties and organic carbon stocks

Mean clay, silt and sand proportions did not vary between organic and conventional farms and were also similar across the different cocoa-age groups (Table 3.3). The soils of the studied organic and conventional cocoa farms are classified as having the texture of loam throughout the 0-30 cm depth. Soil bulk density ranged from 1.15 – 1.29 g cm^{-3} and increased significantly with depth ($F_{1, 94}$ = 6.45, p = 0.013; Table 3.3). However, similar mean soil bulk densities for the 0-30 cm layer was recorded for both organic and conventional farms as well as across the cocoa-age groups.

Table 3.3 Grand mean (± SEM) of soil particle size fractions and bulk density for farm type (n = 24), cocoa-age group (n = 24) and soil depth (n = 48) at Suhum.

Factor	**Treatment**	**Clay (%)**	**Silt (%)**	**Sand (%)**	**Bulk density (g cm^{-3})**
Farm type	Organic	12.08 ± 1.16	48.05 ± 2.83	39.88 ± 3.71	1.28 ± 0.06
	Conventional	12.62 ± 1.94	41.05 ± 3.29	46.32 ± 4.99	1.15 ± 0.04
Cocoa-age group	Young	11.86 ± 1.74	42.83 ± 3.77	45.31 ± 5.31	1.17 ± 0.06
	Mature	9.73 ± 1.5	42.92 ± 4.00	47.36 ± 5.17	1.29 ± 0.07
	Old	15.47 ± 2.32	47.91 ± 3.81	36.63 ± 5.65	1.17 ± 0.05
Soil depth	0-15 cm	12.71 ± 1.22	45.25 ± 2.50	42.05 ± 3.50	1.15 ± 0.03
	15-30 cm	11.99 ± 1.18	43.86 ± 2.52	44.15 ± 3.49	1.28 ± 0.04

In terms of soil depth, the concentration of carbon in the topsoil (0-15 cm) was 58% higher compared to subsoil (15-30 cm) (Topsoil 1.90 ± 0.08 vs. Subsoil 1.20 ± 0.07 %; $F_{1, 94} = 42.74$, $p < 0.001$). Total soil organic carbon stocks were 20% greater in organic farms compared to conventional farms (Org. 59.7 ± 3.4 vs. 49.7 ± 3.3 Mg C ha^{-1}; $F_{1, 42} = 4.5$, $p = 0.04$). Organic farms stocked more carbon in topsoil (0-15 cm) than conventional farm but not the 15-30 cm layer (Figure 3.3; $F_{1, 42} = 6.08$, $p = 0.018$). Soil carbon stocks were greater in the topsoil (32.36 ± 1.62) than the subsoil (22.34 ± 1.20) ($F_{1, 94} = 25.13$, $p < 0.001$) but were similar across the cocoa-age groups.

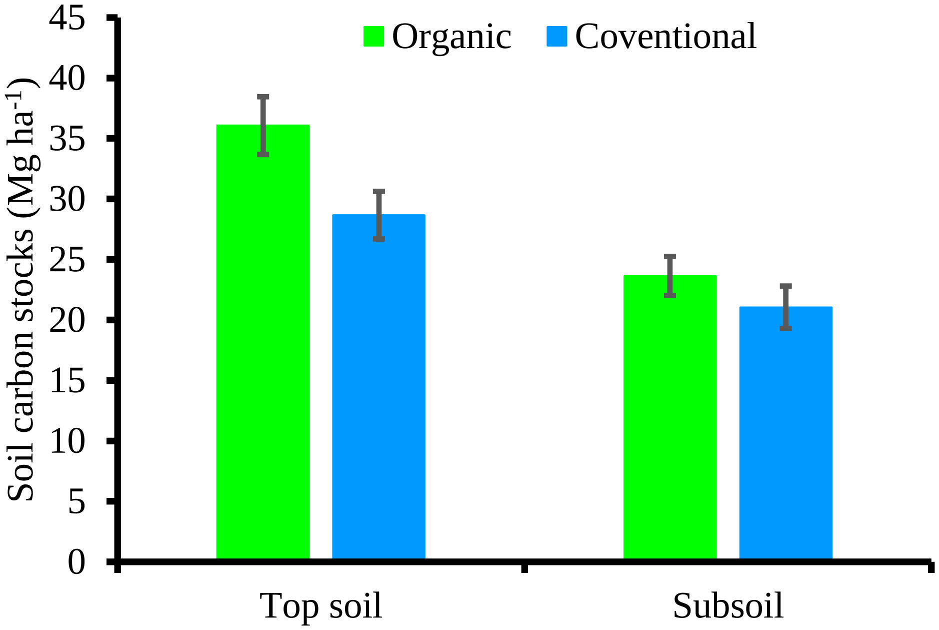

Figure 3.3 Soil organic carbon stocks in top and subsoils of organic and conventional farms at Suhum.

3.3.4 Total carbon stocks, CO_2 equivalent and monetary value

The overall mean carbon stocks (vegetation and soils) for farms under organic management (108.65 Mg C ha^{-1}, 95% CI = 97.44, 123.39) and conventional management (76.30 Mg C ha^{-1}, 95% CI = 67.27, 88.82) were significantly different ($F_{1, 42} = 15.42$, $p < 0.001$). Shade species accumulated 77% of total biomass (aboveground plus belowground) on organic farms and 57% of total biomass on conventional farms. With regards to total carbon stocks, shade species, cocoa trees and litter respectively accounted for 35, 9 and 2% on organic farms and 20, 13 and 2% on conventional farms. Soils stored 55% of total carbon stocks under organic management and 65% under conventional management. The young, mature and old cocoa farms stored similar overall mean carbon stocks.

The rate of avoided CO_2 emission through C accumulation in the biomass of young and old organic cocoa farms were 1.8-fold and 1.7-fold respectively greater than conventional farms (Table 3.4; $F_{1, 42} = 15.44$, $p < 0.001$). Similarly, the monetary value of the CO_2 equivalent of the rate of biomass carbon accumulation in young and old organic cocoa systems were 2.1-fold and 1.9-fold respectively higher in comparison to conventional systems ($F_{1, 42} = 15.44$, $p < 0.001$).

Table 3.4 Monetary value of CO_2 equiv. of biomass C and accumulation rate in organic and conventional cocoa agroforests at Suhum

Farm type	**Cocoa -age group**	**CO_2 equiv. of C stocks (Mg CO_2-eq. ha^{-1})**	**CO_2 equiv. of C stocks rate (Mg CO_2-eq. ha^{-1} yr^{-1})**	**Value of CO_2 equiv. of C stocks (US \$ ha^{-1})**	**Value of CO_2 equiv. of C stocks rate (US \$ ha^{-1} yr^{-1})**
Organic	Young	391.07	32.87	1955.35	208.07
	Mature	416.10	17.57	2080.51	104.65
	Old	454.66	12.45	2273.28	74.58
Conventional	Young	248.38	18.09	1241.91	99.60
	Mature	374.84	16.77	1874.22	89.25
	Old	277.51	7.44	1387.55	39.08

Mg CO_2 = Mg C x 3.67; Price (US\$) = 5 US\$ $[\text{Mg } CO_2]^{-1}$

3.4 Discussion

3.4.1 Aboveground and belowground biomass carbon stocks

The hypothesis of finding greater vegetation carbon stocks on organic farms than conventional farms was supported by the results. Whilst the present study found greater above and below ground carbon stocks on organic farms compared to conventional farms, the study of Schneidewind *et al.* (2018) found no significant differences; the disparity is possibly because their study was done in younger cocoa systems (3 and 7 years) compared to the present study. The integration of shade species into organic cocoa farming, as it is in the study area, enhances the potential of cocoa agroforestry systems to capture and store relatively large amounts of carbon. According to Somarriba *et al.* (2013) dry and humid forests within the ecological range of cocoa store 23-63 Mg C ha^{-1} and 75-275 Mg C ha^{-1} of carbon respectively in their aboveground biomass. Similarly, Wade *et al.* (2010) reported mean aboveground carbon stocks of 155 Mg C ha^{-1} for Atewa Forest Reserve, an upland evergreen forest in the same region where the present study was conducted. The aboveground carbon stocks of organic farms in the present study falls within the range for dry forests; it is half of the minimum value reported for humid forests; and a quarter of the mean aboveground C stocks of the upland evergreen forest in the region. Thus, the maintenance of the vegetation of existing cocoa agroforestry systems as well as the conversion of agricultural lands and no-shade cocoa systems to organic cocoa agroforests could be a management strategy to capture and store large quantities of carbon in smallholder systems.

The fact that the carbon stocks of cocoa trees, coarse roots of cocoa trees and litter were similar on organic and conventional farms demonstrate that the main driver of the variation in carbon stocks is the shade species component (Figure 3.1; Table 3.2). The contribution of shade species to aboveground biomass accumulation and carbon storage was 81% for multi-shade cocoa systems in Indonesia (Rajab *et al.,* 2016), 82% in Central American cocoa systems (Somarriba *et al.,* 2013) and nearly 90% for Cameroonian cocoa systems (Saj *et al*., 2017); shade species on organic but not conventional farms contributed similarly to aboveground biomass carbon as in these studies. Farmers maintain shade species on their cocoa farms for ecological (e.g. shade and N fixation), economic (e.g. valuable timber and commercial fruits) and domestic (e.g. local construction material and medicinal plants) purposes (Wade *et al.,* 2010; Oke and Olatiilu, 2011; Dawoe *et al.,* 2016; Rajab *et al.,* 2016). The most important shade tree species were also the shade tree species that contributed highly to vegetation carbon stocks (Tables 3.2). Since shade species are the major drivers of biomass carbon stocks (Figures 3.1 and 3.3; Schroth *et al.*, 2015; Schroth *et al.*, 2016), carbon schemes that target and promote the inclusion of shade trees in cocoa systems can achieve optimal carbon storage results and at the same time contribute to meeting the needs of farmers and their cocoa. Litter biomass carbon and its contribution to total carbon stocks corroborated with previous studies (Somarriba *et al.,* 2013; Soto-Pinto and Aguirre-Dávila, 2015; Mohammed *et al.*, 2016).

The mean cocoa biomass carbon and their contribution to total aboveground biomass carbon were much lower than those reported for Bolivian cocoa agroforestry systems (Jacobi *et al.,* 2014) and Cameroonian cocoa systems (Norgrove and Hauser, 2013). The results are however comparable to the range reported by both Somarriba *et al.* (2013) for Central American cocoa systems and Dawoe *et al.* (2016) for cocoa in the Ashanti, Brong-Ahafo and Western Regions of Ghana, close to the mean values reported by Mohammed *et al.* (2016), but higher than the mean cocoa biomass carbon reported by Schneidewind *et al.* (2018) for organic and conventional farms. Cocoa age, variety and density influences carbon capture and storage in cocoa trees and may explain the differences in mean cocoa biomass carbon as reported by various authors. Furthermore, nutrient availability, climatic conditions and soil properties vary widely among the cited studies and the present study, thus limiting direct comparison.

3.4.2 Soil organic carbon stocks

The results show that organic farms stocked more carbon in topsoil (0-15 cm) and the overall 0-30 cm but not the 15-30 cm layer due to litter inputs with greater carbon concentration in organic cocoa agroforestry systems (Figure 3.3). This finding supported the hypothesis of the study and it concurs with other workers (Soto-Pinto and Aguirre-Dávila, 2015; Blanco-Canqui *et al.* 2017). Specifically, Blanco-Canqui *et al.* (2017) reported greater soil organic carbon stocks for agricultural farms under organic management compared to those under conventional management for the 0-15 cm layer. A meta-analysis by Gattinger *et al.* (2012) using datasets from mainly temperate zones showed that organic farming stocked greater amounts of carbon in the topsoil (0-15 cm) than conventional farming. In Mexican coffee polycultures, Soto-Pinto and Aguirre-Dávila (2015) found significantly higher stocks of carbon in organic coffee polycultures than nonorganic coffee polycultures in soil (0-30 cm). The finding that soils stored at least 55% of total carbon stocks regardless of farm management type (organic or conventional) is consistent with the assertion that soil is a major carbon pool in cocoa systems (Wade *et al.,* 2010; Gattinger *et al.,* 2012; Somarriba *et al.,* 2013; Jacobi *et al*., 2014; Soto-Pinto and Aguirre-Dávila, 2015; Silatsa *et al.*, 2017). Soil organic carbon stocks significantly decreased with depth as reported in other studies (Soto-Pinto and Aguirre-Dávila, 2015; Mohammed *et al.,* 2016).

3.4.3 Biomass, carbon stocks and cocoa-age groups

The finding that cocoa aboveground and belowground biomass carbon stocks were highest in old cocoa farms, medium in mature farms and lowest in young farms is consistent with the findings of Saj *at al.* (2017) from a study of central Cameroonian cocoa plantations. The differences in cocoa carbon stocks may stem from differences in cocoa tree density, age or both. Silatsa *et al.* (2017) reported that although carbon stocks in various components (soil, trees, understory, litter and total) tended to increase with age in both fallow and cocoa systems, it only reached statistically significant levels at 15-20 years and beyond. They further observed that total carbon stocks increased as the cocoa system mature. Contrary to their findings, no significant differences were found among the studied cocoa-age groups. The fact that there were no significant differences in shade trees and total carbon stocks across cocoa-age groups may reflect the active management of the shade component as the cocoa system matures (Dawoe *et al.,* 2016).

3.4.4 Total carbon stocks, CO_2 equivalent and monetary value

The cocoa management approach affected vegetation biomass and the capture and storage of carbon in various pools. The results of the present study demonstrate that organic cocoa agroforestry systems hold a greater potential to accumulate biomass and carbon stocks in vegetation (aboveground and belowground components) and soils than conventional cocoa agroforestry systems. Organic management of cocoa is thus a crucial factor in the capture and storage of carbon in various pools in cocoa agroforestry systems. The organic systems produced more biomass, recycled and stored greater amounts of carbon in shade species and soils than the conventional systems (Figures 3.1 and 3.3).

Given that the rate of carbon accumulation was 49% higher in organic cocoa agroforests compared to conventional farms (Table 3.4), organic cocoa agroforests are promising in the context of serving as carbon sinks and could have a potential to mitigate climate change. The hypothesis of the present study which was that organic farms would demonstrate a geater potential to provide additional income under REDD+ activities therefore holds. The cocoa sector has been added to Ghana’s carbon accounting budget (Mohammed *et al.*, 2016). Organic cocoa farmers receive premium price for their cocoa; based on Table 3.4, they may also soon enjoy additional income from sale of carbon credits and incentives from related schemes such as the Joint Implementation and Clean Development Mechanisms and Reduced Emissions Deforestation and

Forest Degradation (REDD+). However, cocoa agroforestry systems are complex dynamic systems (Asare and Anders, 2016) thus carbon schemes must capture the dynamic complexities of these systems to be effective. For example, farmers constantly plant cocoa and shade trees to replace aged, diseased or damaged trees which make the cocoa systems heterogenous in terms of age and this translates to different carbon accumulation rates *per* tree. Thus, quick, cheap and precise methods of estimating carbon accumulation rates *per* tree in cocoa systems, based on which the system's carbon accumulation rates are estimated are urgently needed.

3.5 Conclusion

The results of the present study demonstrate the potential of organic cocoa agroforestry systems to provide the environmental function of carbon sequestration. The results show that organic cocoa agroforestry systems hold a greater potential to accumulate biomass and carbon stocks in vegetation (aboveground and belowground components) and soils than conventional cocoa agroforestry systems and could potentially generate additional income through the sale of carbon credits. We also demonstrate a greater potential on organic farms to generate additional income through the sale of carbon credits than conventional systems; this might lead to diversified income and enhanced livelihoods for organic farmers. Organic management of cocoa is thus a crucial factor in the capture and storage of carbon in various pools in cocoa agroforestry systems. Organic management of cocoa agroforestry systems enhances biomass accumulation and carbon storage in vegetation and soils, and thus have the potential to contribute to mitigation of climate change. It is concluded that the inclusion of smallholder organic cocoa systems in carbon schemes such as REDD+ is justified.

4 TEMPORAL CHANGES IN LITTERFALL AND POTENTIAL NUTRIENT RETURN IN COCOA AGROFORESTRY SYSTEMS UNDER ORGANIC AND CONVENTIONAL MANAGEMENT IN GHANA

Abstract

Litterfall is a critical link between vegetation and soils by which nutrients are returned to the soils, thus the amount and pattern of litterfall regulates nutrient cycling, soil fertility and primary productivity in all ecosystems. The present study quantified, analysed and compared macro- and micro-nutrient return through litterfall in organic and conventional cocoa agroforestry systems at Suhum, Ghana. The study further assessed the contribution of shade tree species to litterfall and nutrient dynamics. The annual pattern of litterfall was affected by seasonality, with a major peak in the dry season and minor peaks during the rainy season. The annual amount of litterfall was similar on both organic (12.4 ± 0.44 Mg ha^{-1} yr^{-1}) and conventional farms (12.7 ± 0.75Mg ha^{-1} yr^{-1}). The monthly deposition of primary macro-nutrients (N, P and K), secondary macro-nutrients (Ca, Mg and S) and micro-nutrients (Na, Al, Mn, Fe, B, Co, Cu, Ni, Zn and Mo) via litterfall varied significantly with time independent of management type, and annual nutrients return were similar in organic and conventional cocoa systems. Shade tree leaf litter accounted for 30-47 % of annual macro- and micro-nutrient deposition (except Ni, Zn and Co) in organic cocoa systems versus 20-35 % in conventional cocoa systems. The results emphasize the complementary role of the different shade tree species which compose organic and conventional cocoa systems in nutrient recycling. The study concludes that organic management of cocoa agroforestry systems ensure nutrients return similar to those

receiving synthetic fertilizer inputs, highlighting its potential to support cocoa production.

4.1 Introduction

The transfer of energy and nutrients between the biological and non-biological components of an ecosystem is crucial for its existence and resilience (Hartemink, 2005; Owusu-Sekyere *et al.*, 2006; Fontes *et al.*, 2014). Litterfall is a critical link between vegetation and soils by which nutrients are returned to the soils, thus the amount and pattern of litterfall regulates nutrient cycling, soil fertility and primary productivity in all ecosystems (Hartemink, 2005; Ofori-Frimpong *et al.*, 2007; Becker *et al.*, 2015). Plant litter acts as an input-output system for organic matter and humus, thus it influences the soil quality of an ecosystem (Hartemink, 2005; Fontes *et al.*, 2014). Litterfall and its attendant processes such as decomposition and nutrient mineralization are key components of the plant-soil system (Kumar, 2008; Becker *et al.*, 2015). Therefore, understanding the dynamics of litterfall in cocoa agroforestry systems is a critical step in ensuring management supports optimal functioning of these systems. The amount and composition of litter in an ecosystem depends on the characteristics of its vegetation and the climatic conditions of the site (Owusu-Sekyere *et al.*, 2006; Wood *et al.,* 2006; Mamani-Pati *et al.*, 2012; Becker *et al.*, 2015) and possibly management approach.

The primary sources of litter in cocoa agroforestry systems are the cocoa and shade trees. The amount of litter produced in cocoa agroforestry systems is moderated by tree density, basal area and canopy cover (Triadiati *et al.*, 2011; Mamani-Pati *et al.*, 2012).

Litterfall production in ecosystems is strongly related to rainfall seasonality, with the dry and rain seasons being the peak periods of litterfall in stands under climates with and without dry season respectively (Owusu-Sekyere *et al.*, 2006; Muoghalu and Odiwe, 2011; Becker *et al.*, 2015). Climatic factors such as low air humidity, high temperature and their interaction moderate litterfall production in cocoa agroforestry systems by stimulating abscisic acid synthesis (Yang *et al.*, 2003; Dawoe *et al.,* 2010; Triadiati *et al.*, 2011). Leaf litterfall is also affected by elevation, wind and foliar diseases (Mamani-Pati *et al.*, 2012; Becker *et al.*, 2015).

The amount and quality of litter produced in an ecosystem depends on soil quality and management (Kumar, 2008; Muoghalu and Odiwe, 2011; Domínguez *et al.,* 2014). Stands on fertile soils produce greater amount and high-quality litter than stands on poor soils due to higher biomass production and/or low rates of nutrient resorption from litter before abscission (Kumar, 2008; Fontes *et al.*, 2014). Wood *et al.* (2006) asserted that soil fertility is positively related to the amount of litterfall, leaf litter quality and the rate of decomposition and nutrient mineralization. Growing plants in natural systems, such as forests, depend solely on nutrient cycling to meet their nutritional needs thus nutrient supply rate and nutrient limitation are moderated via species composition and diversity and moisture supply (Wood *et al.*, 2006; Kumar, 2008; Becker *et al.*, 2015). However, in agroforestry systems such as cocoa agroforestry, the management approach may affect litter decomposition, which in turn, enhances or reduces nutrient supply rate through nutrient cycling (Ofori-Frimpong *et al.*, 2007; Fontes *et al.*, 2014; Becker *et al.*, 2015). For example, non-agrochemical use was enough to enhance litter decomposition and nutrient mineralization in organic systems compared to conventional systems due to the presence of more well adapted decomposer communities in organic systems (Domínguez *et al.,* 2014). Moreover, Muoghalu and Odiwe (2011) attributed greater accumulation of litter on the floor of cocoa stands than kola nut plantations to greater agrochemicals use in cocoa systems and differences in litter quality. In Tanzanian agroforestry systems, Becker *et al.*, (2015) reported greater macronutrient content and deposition rates than natural forests and attributed the differences to fertilization and associated changes in dominant tree species. Thus, dominant tree species in cocoa systems could regulate nutrient return.

Leaf litter is the major component of litterfall material in agroforestry systems, comprising more than 60 % of total annual litterfall (Muoghalu and Odiwe, 2011; Fontes *et al.*, 2014). Cocoa leaf litter predominates leaf litterfall in cocoa agroforestry plantations (Dawoe *et al.*, 2010) but inputs from the shade tree component can improve litter quality and enhance nutrient cycling in these systems. For example, leaves from the middle and upper canopy strata are a mechanism for returning nutrients to the soil in certified organic coffee systems in Bolivia (Mamani-Pati *et al.*, 2012). The shade trees enhance the capture of solar energy and at the same time increase the absorption and retention of carbon and nitrogen in both below- and above-ground components (Hartemink, 2005; Ofori-Frimpong *et al.*, 2007; Fontes *et al.*, 2014; Becker *et al.*, 2015;). Fallen leaves on the floor of agroforestry systems cover the soil and thereby maintain soil moisture and reduces erosion and serve as habitats for beneficial organisms (Mamani-Pati *et al.*, 2012).

Cocoa in Ghana is mostly cultivated under a variety of shade trees and are either organically or conventionally managed. The conventional systems depend on synthetic agrochemicals to maintain soil fertility, suppress weeds and control pests and diseases whilst the organic systems rely on ecological processes and organic products for these services. Increasingly, there is a trend towards the maintenance of high shade tree diversity on the organic farms (Chapter 2, Page 38-47) possibly because farmers perceive shade trees as a cheaper means to replenishing soil nutrients. Moreover, the use of shade trees is generally encouraged in organic cocoa systems in Ghana as a means to improve soil fertility (Djokoto *et al.*, 2016). Many workers have assessed nutrient returns through litter inputs in cocoa systems (e.g. Owusu-Sekyere *et al.*, 2006; Ofori-Frimpong *et al.*, 2007; Dawoe *et al.*, 2010; Muoghalu and Odiwe, 2011) but studies focusing on organic and conventional cocoa systems are rare thus making it difficult to evaluate the impact of organic cocoa production on nutrient cycling. The present study quantified and analysed annual patterns of nutrient deposition via litterfall in organic and conventional cocoa agroforestry systems. Specifically, it explored the effect of management type and seasonality on litterfall and nutrient deposition, and the contribution of shade tree species to nutrient return via litterfall. The study postulated that litterfall and nutrient deposition will follow a temporal pattern with greater nutrient concerntrations and stocks during the rainy seasons than the dry season. It was also posited that litterfall from shade tree species and their contribution to annual nutrient deposition will be greater on organic systems than conventional systems.

4.2 Methods

4.2.1 Selection of cocoa farms

The study area has been described in Chapter 2 (Page 27-30). Two cocoa communities (Nsuta-Wawase and Kuano) were randomly selected from a list of cocoa producing areas in Suhum which was provided by the local office of Ghana COCOBOD, the regulator of the sector. Cocoa farms were randomly selected from separate lists of organic and conventional farmers in the two cocoa communities. Selected farmers consented to the research and plots (25 m x 25 m) were established on their farms. The age of the cocoa plantations in which the present study was conducted ranged from 15-30 years in each farm type.

4.2.2 Collecting, processing and chemical analysis of litterfall

To collect litterfall, four (4) wooden litter boxes of dimensions 50 cm x 50 cm x 30 cm with a 2 mm fibre netting at the bottom were installed in each plot (Dawoe *et al.* 2010). The boxes were 40 cm above the ground.

The litter traps were emptied every month from March 2017 to February 2018. The samples were separated into four fractions; cocoa leaves, shade leaves, twigs and small branches (TSB), and reproductive parts and others (RPO) (Dawoe *et al.* 2010). Each fraction was weighed to determine their wet weight and oven-dried at 70 ºC for 48 hrs to determine their dry weights.

The nutrient composition of the oven-dried litter fractions was determined after milling with agate ball mill (Retch PM 400) for 15 minutes at 290 rpm. Total C and N contents (%) were estimated by using CN analyser (Thermo Scientific™ Flash™ 2000 Organic Elemental Analyzer (OEA)) and macro- and micro-nutrients via ICP-MS (Thermo Scientific™ iCAP™ TQ). Prior to the ICP-MS, the samples (0.2 g) were microwave-digested after adding 6 ml of concentrated NHO_3 acid. Chemical analysis for total C and N contents was conducted quarterly whlist chemical analysis for macro- and micro-nutrient contents was conducted on monthly basis.

4.2.3 Data analysis

Total monthly litterfall and nutrient contents were analysed using repeated measures ANOVA in GenStat (vs. 19). To correct for violations of sphericity, the degrees of freedom were multiplied by Greenhouse-Geisser epsilon. Where interaction terms were not significant, only main effects were considered in results and discussion. The effect of farm management type on annual total litterfall and fractional litterfall was analysed via one-way ANOVA. The assumptions of normality were assessed through visual inspection of scatter plots and histograms of data and residuals; variables which were not normally distributed were Box-Cox transformed. Spearman rank correlation was used to assess the strength and direction of the monotonic relationship between annual fractional litterfall and both stand characteristics and nutrient deposition in the two farm types. Data on stand characteristics (canopy cover, tree density, stand basal area, total basal area, species richness and Shannon diversity) have been presented in Chapter 2 (Page 30-47). Differences in mean values were considered significant at $p < 0.05$.

4.3 Results

4.3.1 Temporal dynamics of litterfall

Monthly litterfall patterns were similar on both organic and conventional farms (Figure 4.1). However, whereas litterfall peaked in both November and March (i.e. at the beginning and at the end of the dry season) on conventional farms, it peaked only in November on organic farms. Three smaller peaks appeared during January (mid-dry season), March (end of dry season), and June (peak major rainy season) on organic farms whilst on conventional farms two smaller peaks appeared during January to February and April to May (i.e. at the beginning of the major rainy season). Mean monthly litterfall was significantly different across time (Greenhouse-Geisser epsilon = 0.5277, $F_{11\ 154} = 8.33$, $p < 0.001$) and it had a significant interaction with management type (Greenhouse-Geisser epsilon = 0.5277, $F_{11\ 154} = 2.26$, $p = 0.048$). The deposition of shade and cocoa leaves were both highest during November on organic farms whilst on conventional farms, cocoa leaf litter production was highest in March and shade tree species leaf litterfall was highest in February.

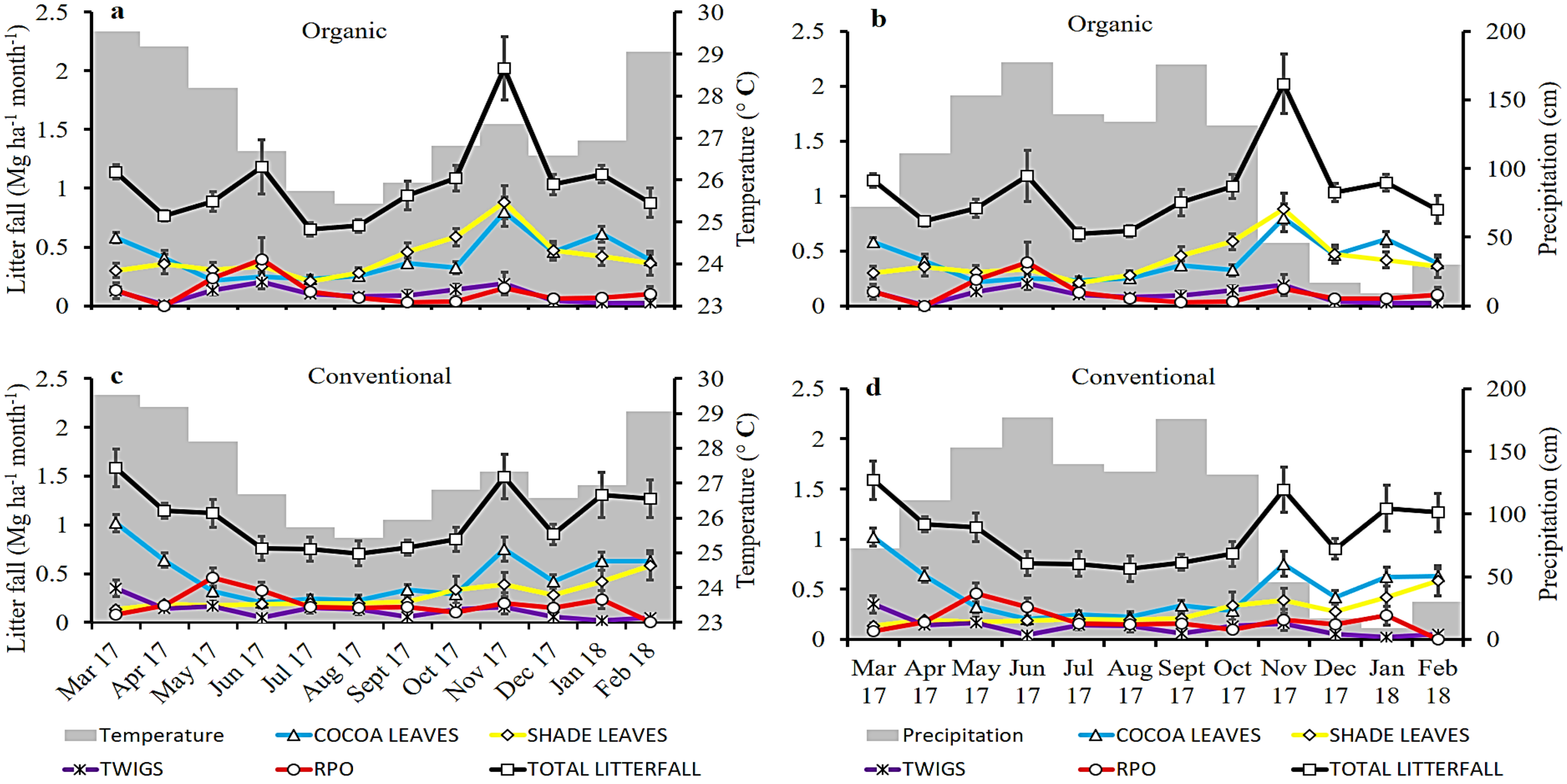

Figure 4.1 Monthly litterfall (Mean ± SEM) from March 2017 to February 2018 on organic and conventional cocoa agroforestry farms at Suhum. Total litterfall (squares) is comprised of leaf litter from cocoa (triangles) and shade tree species (diamonds), twigs and small branches (asterisks), and reproductive parts and others (RPO, circles). Long term mean monthly temperature (panels a and c) and precipitation (panels b and d) (1901 to 2015; World Bank Group, 2018 and Web 2) are indicated as bars.

4.3.2 Nutrient contents and temporal dynamics

The concentration of macro-nutrients in litterfall were generally higher in May, which coincides with the major rainy season, and tended to gradually decrease overtime (Appendix Table 4; Appendix Figure 1). The concentration of the micro-nutrients Al, Fe, Na, Co, Ni, Zn, Mo and Cu were highest in July-August (i.e. at the end of the major rainy season) whiles Fe, Co and B concentrations in monthly litterfall remained similar overtime (Appendix Table 4; Appendix Figure 2). The interactive effect of farm type and time on the concentrations of deposited nutrients were significant for both macro- and micro-nutrients, except N, Fe, Mn and Co (Appendix Table 4); concentrations of deposited nutrients were generally higher in March on organic farms than conventional farms but lower in April. That means during the rainy season, concerntrations of deposited nutrients were broadly higher but similar on both farm types and during the dry season, nutrient concentrations were lower and differed between farm types depending on the month.

The mean stock of monthly deposition of primary macro-nutrients (N, P and K), secondary macro-nutrients (Ca, Mg and S) and micro-nutrients (Na, Al, Mn, Fe, B, Co, Cu, Ni, Zn and Mo) via litterfall varied significantly with time regardless of farm management type (Tables 4.1 and 4.2; Figures 4.2 and 4.3). There was a significant interactive effect of farm type and time on the deposition of the macro-nutrients, Ca and S, and the micro-nutrients, Na and B. Deposited stocks of Ca, S, B and Na nutrients were generally higher on organic farms than conventional farms during June and October which coincides with the major and minor rain seasons, respectively but lower during February (i.e. during the dry season) (Figures 4.2 b and f; 4.3 b and g).

Table 4.1 Repeated measures ANOVA of stocks of monthly macro-nutrient deposition and farm type. ‘a’ degrees of freedom is $F_{1,\ 14}$ for all parameters except C and N ($F_{1,\ 10}$); ‘b’ degrees of freedom is $F_{11,\ 154}$ for all parameters except C and N ($F_{3,\ 30}$). The given ‘b’ d.f. were multiplied by the Greenhouse-Geisser epsilon values (GGE) before the estimation of *p*-values shown in parenthesis and significant values ($p < 0.05$) are italicised.

	F-value				
Parameter	**Nutrient**	**GGE**	**Farm type^{a}**	**Month^{b}**	**Farm type x month^{b}**
Primary macro-nutrients	C	0.5960	0.55 (0.476)	6.75 (*0.008*)	1.66 (0.219)
	N	0.6931	2.86 (0.122)	4.30 (*0.026*)	2.66 (0.092)
	P	0.5519	1.00 (0.334)	4.08 (*0.001*)	1.78 (0.112)
	K	0.5826	< 0.01 (0.979)	12.09 (< *0.001*)	1.37 (0.233)
Secondary macro-nutrients	Mg	0.4997	0.12 (0.730)	9.51 (< *0.001*)	2.13 (0.065)
	Ca	0.6032	0.08 (0.782)	10.83 (< *0.001*)	2.93 (*0.009*)
	S	0.5147	< 0.01 (0.981)	9.21 (< *0.001*)	2.79 (*0.018*)

Table 4.2 Repeated measures ANOVA of monthly micro-nutrient deposition and farm type. ‘a’ degrees of freedom is $F_{1,\ 14}$ for all parameters; ‘b’ degrees of freedom is $F_{11,\ 154}$ for all parameters. The given ‘b’ d.f. were multiplied by the Greenhouse-Geisser epsilon values (GGE) before the estimation of p-values shown in parenthesis and significant values ($p < 0.05$) are italicised.

		F-value		
Micro-nutrient	**GGE**	**Farm type^{a}**	**Month^{b}**	**Farm type x month^{b}**
Na	0.4412	1.07 (0.319)	9.53 (< *0.001*)	2.43 (*0.045*)
Al	0.5419	0.59 (0.455)	4.22 (< *0.001*)	1.87 (0.096)
Mn	0.4911	< 0.01 (0.950)	6.85 (< *0.001*)	1.44 (0.217)
Fe	0.5119	1.25 (0.282)	3.55 (*0.004*)	1.54 (0.179)
B	0.5365	0.01 (0.941)	15.26 (< *0.001*)	2.50 (*0.029*)
Co	0.4770	0.01 (0.922)	5.86 (< *0.001*)	0.64 (0.677)
Ni	0.4420	1.06 (0.320)	4.26 (0.002)	1.45 (0.219)
Cu	0.5300	0.07 (0.794)	4.65 (< 0.001)	1.81 (0.109)
Zn	0.5519	< 0.01 (0.985)	5.58 (< 0.001)	1.44 (0.215)
Mo	0.4911	< 0.01 (0.950)	6.85 (< 0.001)	1.44 (0.217)

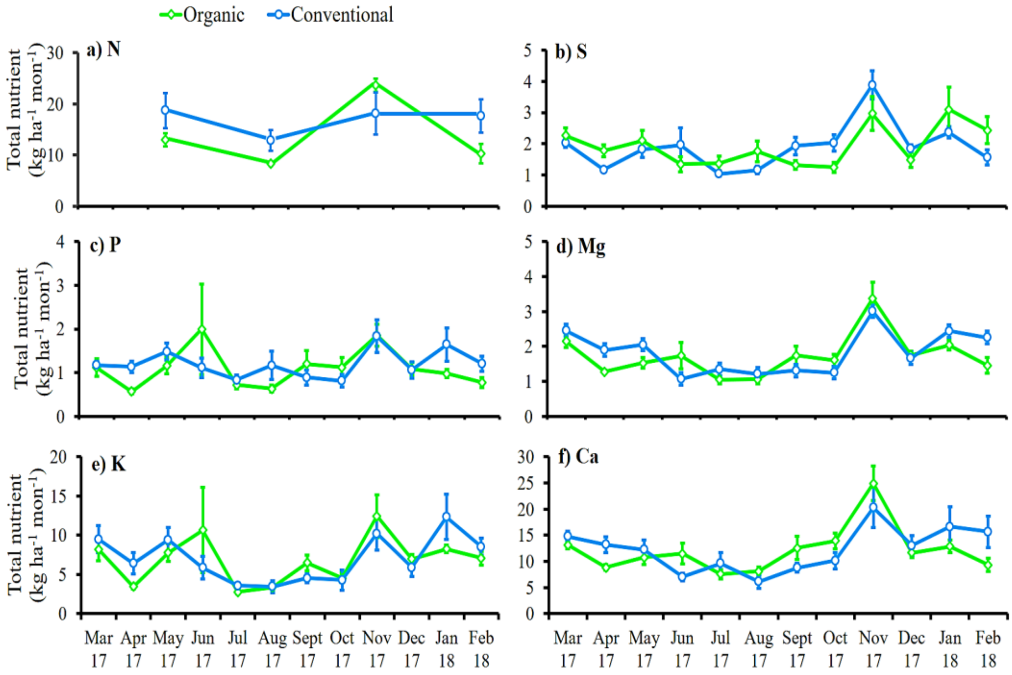

Figure 4.2 Pattern of monthly macro-nutrients deposition (panels a-f, mean ± SEM) in organic and conventional cocoa agroforest systems at Suhum.

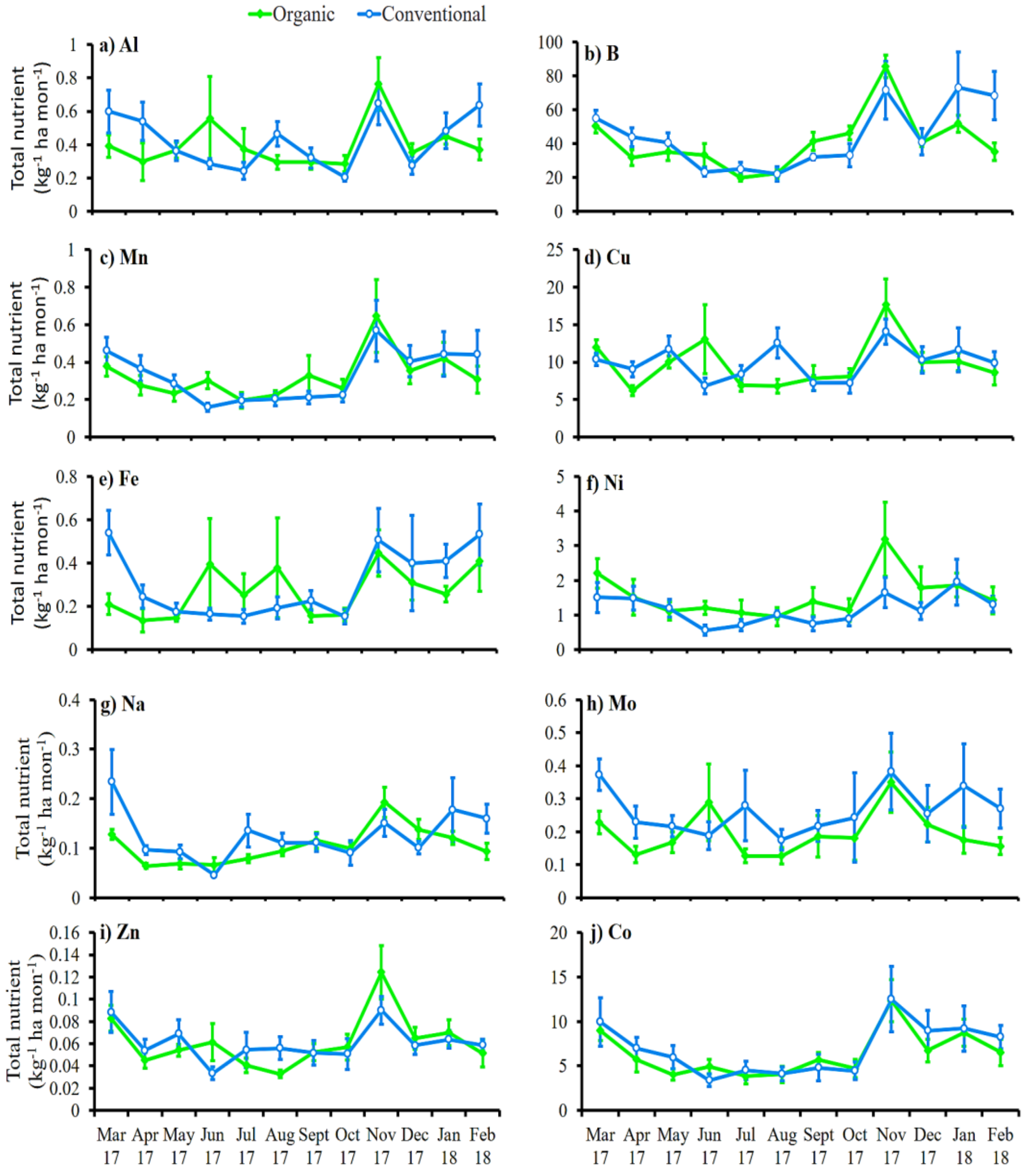

Figure 4.3 Pattern of monthly micro-nutrients deposition (panels a-j, mean ± SEM) in organic and conventional cocoa agroforestry systems at Suhum.

Spearman's rank correlation between monthly nutrient deposition for all nutrients (except Cu and P) and fractional litterfall showed a medium to strong positive correlation with cocoa leaves (r^2 = 0.64-0.92, $p < 0.03$) on conventional farms (Table 4.3). On organic farms, the nutrients Ca, S, Mg, B and Mn were positively and significantly correlated with both cocoa and shade tree species leaf litterfall whilst Na, Co, Ni, and Zn were significantly correlated with cocoa leaves but not with shade tree species litter, TSB or RPO. The primary macro-nutrient, P, significantly correlated with TSB; Al and Cu with RPO; and K showed a marginal significant correlation with RPO.

Table 4.3 Spearman rank correlation between monthly nutrient deposition (kg ha^{-1} mon^{-1}) and monthly fractional litterfall (Mg ha^{-1} mon^{-1}) on organic and conventional cocoa agroforestry farms at Suhum. Correlation coefficient (r^{2}) are shown with p-values presented in parenthesis and significant correlations ($p < 0.05$) italicised. TSB and RPO refers to the fractions twigs and small branches and reproductive parts and others, respectively.

	Organic				**Conventional**			
Nutrient	**Cocoa leaves**	**Shade leaves**	**TSB**	**RPO**	**Cocoa leaves**	**Shade leaves**	**TSB**	**RPO**
P	-0.007 (0.983)	0.427 (0.167)	0.797 (*0.002*)	0.469 (0.124)	0.524 (0.080)	0.126 (0.697)	0.133 (0.681)	0.294 (0.354)
K	0.455 (0.138)	0.364 (0.245)	0.413 (0.183)	0.573 (0.051)	0.755 (*0.005*)	0.154 (0.633)	0.077 (0.812)	0.280 (0.379)
Mg	0.727 (*0.007*)	0.587 (*0.045*)	0.308 (0.331)	0.154 (0.633)	0.881 (< *0.001*)	0.224 (0.484)	0.343 (0.276)	0.007 (0.983)
Ca	0.608 (*0.036*)	0.720 (*0.008*)	0.441 (0.152)	0.021 (0.948)	0.867 (< *0.001*)	0.448 (0.145)	0.084 (0.795)	-0.021 (0.948)
S	0.629 (*0.028*)	0.615 (*0.033*)	0.441 (0.152)	0.175 (0.587)	0.671 (*0.017*)	0.238 (0.457)	0.119 (0.713)	0.119 (0.713)
B	0.748 (*0.005*)	0.706 (*0.010*)	0.203 (0.527)	-0.021 (0.948)	0.867 (< *0.001*)	0.462 (0.131)	-0.007 (0.983)	-0.021 (0.948)
Na	0.713 (*0.009*)	0.538 (0.071)	0.098 (0.762)	-0.070 (0.829)	0.636 (*0.026*)	0.322 (0.308)	0.112 (0.729)	-0.350 (0.265)

Table 4.3 Continued

Al	0.343 (0.276)	-0.028 (0.931)	0.315 (0.319)	0.699 (*0.011*)	0.748 (*0.005*)	0.126 (0.697)	0.210 (0.513)	-0.070 (0.829)
Mn	0.888 (< *0.001*)	0.608 (*0.036*)	-0.021 (0.983)	0.007 (0.983)	0.916 (< *0.001*)	0.343 (0.276)	0.189 (0.557)	-0.168 (0.602)
Fe	0.273 (0.391)	0.168 (0.602)	0.168 (0.602)	0.455 (0.138)	0.860 (< *0.001*)	0.231 (0.471)	0.042 (0.897)	-0.294 (0.829)
Co	0.958 (< *0.001*)	0.531 (0.075)	-0.154 (0.633)	-0.049 (0.880)	0.916 (< *0.001*)	0.287 (0.366)	0.224 (0.484)	-0.070 (0.829)
Ni	0.930 (< *0.001*)	0.531 (0.075)	-0.119 (0.713)	-0.042 (0.897)	0.839 (< *0.001*)	0.252 (0.430)	0.182 (0.572)	0.007 (0.983)
Cu	0.427 (0.167)	0.336 (0.286)	0.538 (0.071)	0.636 (*0.026*)	0.399 (0.199)	0.063 (0.846)	0.392 (0.208)	0.105 (0.746)
Zn	0.650 (*0.022*)	0.531 (0.075)	0.413 (0.183)	0.308 (0.331)	0.657 (*0.020*)	0.091 (0.779)	0.448 (0.145)	0.014 (0.966)
Mo	0.469 (0.124)	0.559 (0.059)	0.573 (0.051)	0.308 (0.331)	0.713 (*0.009*)	0.413 (0.183)	0.196 (0.542)	-0.189 (0.557)

4.3.3 Annual litterfall and nutrient deposition

The annual mean total litterfall was similar in both organic and conventional cocoa agroforestry systems (Org. 12.4 ± 0.44 Mg ha^{-1} yr^{-1} vs. Con. 12.7 ± 0.75 Mg ha^{-1} yr^{-1}, $p > 0.05$). In terms of annual fractional litterfall, mean leaf litter from shade tree species was significantly higher (50 %) in organic systems compared to conventional systems (Figure 4.4; $F_{1\ 14} = 4.76$, $p = 0.047$). Whereas cocoa leaves (45.0 %) were the predominant fraction of litterfall from conventional farms, both shade leaves (40.0 %) and cocoa leaves (39.4 %) dominated litterfall from organic farms. Annual deposition of twigs and small branches was less than 12 % of total litterfall on both farm types. Spearman's rank correlation of stand characteristics and annual fractional litterfall showed that leaf litter from shade tree species was positively related to canopy cover, tree density, stand basal area, total basal area, species richness and Shannon diversity (Table 4.4). Reproductive parts and others (RPO) was negatively related to stand basal area, total basal area, species richness and Shannon diversity. Cocoa leaf litter was negatively correlated with canopy cover.

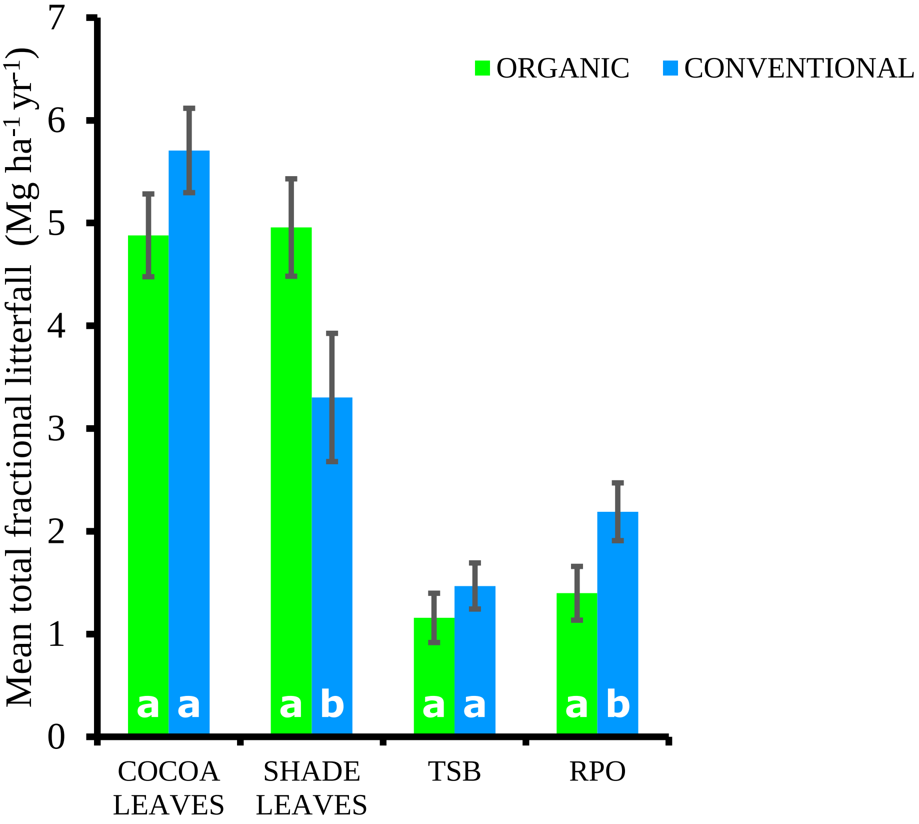

Figure 4.4 Annual fractional litterfall (2017-2018, Mean ± SEM) in organic and conventional cocoa agroforestry systems at Suhum. Litter fractions with different letters indicate significant difference ($p < 0.05$) based on one-way ANOVA. TSB and RPO are twigs and small branches and reproductive parts and others litter fractions, respectively.

Table 4.4 Spearman's rank correlation between selected stand characteristics and mean annual fractional litterfall of organic and conventional cocoa agroforestry systems at Suhum. Correlation coefficient (r^2) are shown with p-values presented in parenthesis and significant values ($p < 0.05$) are italicised. RPO is reproductive parts and others litter fraction, and TSB is twigs and small branches.

Parameter	**Cocoa leaves (Mg ha^{-1} yr^{-1})**	**Shade leaves (Mg ha^{-1} yr^{-1})**	**TSB (Mg ha^{-1} yr^{-1})**	**RPO (Mg ha^{-1} yr^{-1})**
Canopy cover (%)	-0.603 (*0.013*)	0.537 (*0.032*)	0.222 (0.408)	-0.199 (0.461)
Strata (no. plot^{-1})	0.072 (0.792)	0.314 (0.236)	0.024 (0.930)	-0.383 (0.144)
Fruit density (no. ha^{-1})	-0.132 (0.625)	0.193 (0.473)	-0.184 (0.494)	-0.388 (0.137)
Tree density (no. ha^{-1})	-0.268 (0.315)	0.602 (*0.014*)	0.097 (0.721)	-0.279 (0.296)
Cocoa density (no. ha^{-1})	0.289 (0.277)	-0.229 (0.394)	-0.125 (0.643)	0.022 (0.935)
Total density (no. ha^{-1})	-0.038 (0.888)	0.071 (0.795)	-0.031 (0.909)	-0.272 (0.307)
Stand basal area (cm^2 ha^{-1})	-0.468 (0.068)	0.771 (< *0.001*)	-0.003 (0.991)	-0.568 (*0.022*)
Cocoa basal area (cm^2 ha^{-1})	0.265 (0.322)	-0.418 (0.107)	-0.179 (0.506)	0.150 (0.579)
Total basal area (cm^2 ha^{-1})	-0.441 (0.087)	0.559 (*0.024*)	-0.244 (0.362)	-0.612 (*0.012*)
Species richness (no. ha^{-1})	-0.252 (0.347)	0.659 (*0.005*)	-0.014 (0.960)	-0.511 (*0.043*)
Shannon diversity (H plot^{-1})	-0.177 (0.513)	0.599 (*0.014*)	-0.077 (0.778)	-0.543 (*0.030*)

Annual macro- and micro-nutrient deposition through litterfall production were similar on both organic and conventional cocoa farms (Table 4.5). However annual P, S, Cu and Mo nutrient return via cocoa leaf litter were 57, 26, 35 and 73 % respectively higher on conventional farms compared to organic farms ($F_{1, 14}$ = 20.03, $p < 0.001$; $F_{1, 14}$ = 5.00, $p = 0.042$; $F_{1, 14}$ = 5.64, $p = 0.032$; $F_{1, 14}$ = 6.85, $p = 0.020$, respectively). The return of the macro-nutrients Mg and S via shade trees leaf litter were 56 and 52 %, respectively, higher on organic farms than conventional farms ($F_{1, 14}$ = 5.77, $p = 0.031$; $F_{1, 14}$ = 4.80, $p = 0.046$, respectively). On conventional farms, the deposition of Mg, Al, Na and B through reproductive parts and others (RPO) litter were 68, 73, 72 and 100%, respectively, greater than organic farms ($F_{1, 14}$ = 4.66, $p = 0.049$; $F_{1, 14}$ = 7.75, $p = 0.015$; $F_{1, 14}$ = 5.34, $p = 0.037$; $F_{1, 14}$ = 5.64 $p = 0.032$, respectively). The return of N through RPO was 100 % greater on conventional farms than organic farms ($F_{1, 10}$ = 6.61, $p = 0.028$). In general, shade trees contributed 30-47 % of total annual macro- and micro-nutrients return on organic farms and 20-35% on conventional farms.

Table 4.5 Annual fractional and total nutrient deposition via litterfall on organic and conventional cocoa agroforestry systems at Suhum. TSB is twigs and small branches, and RPO is reproductive parts and others. Columns with different letters (superscript and in bold) within each litter fraction category indicates significant differences in mean values (One-way ANOVA, $p < 0.05$) between organic (org.) and conventional (con.) cocoa farms, and those without letters indicate no significant differences.

	Cocoa		**Shade**		**TSB**		**RPO**		**Total**	
Nutrient	**Org.**	**Con.**	**Org.**	**Con.**	**Org.**	**Con.**	**Org.**	**Con.**	**Org.**	**Con.**
					kg ha^{-1} yr^{-1}					
N	58.2	81.4	75.9	53.8	9.9	23.7	21.4$^{\mathbf{a}}$	43.1$^{\mathbf{b}}$	165.4	202.0
P	3.0$^{\mathbf{a}}$	4.7$^{\mathbf{b}}$	5.8	4.3	1.2	1.8	3.1	3.6	13.2	14.3
K	28.2	34.7	29.6	21.1	7.9	8.9	16.2	19.3	81.9	84.0
Mg	10.2	12.2	6.9$^{\mathbf{a}}$	4.4$^{\mathbf{b}}$	1.7	1.9	2.0$^{\mathbf{a}}$	3.4$^{\mathbf{b}}$	20.8	22.0
Ca	57.8	70.7	61.3	42.6	13.8	14.3	12.2	19.9	145.1	147.5
S	8.1$^{\mathbf{a}}$	10.1$^{\mathbf{b}}$	10.4$^{\mathbf{a}}$	6.8$^{\mathbf{b}}$	1.6	2.0	2.7	4.2	22.8	23.1
Al	1.6	2.1	2.1	1.5	0.5	0.5	0.6$^{\mathbf{a}}$	1.0$^{\mathbf{b}}$	4.8	5.1
Mn	2.1	2.3	1.3	0.9	0.3	0.2	0.3	0.5	3.9	4.0
Fe	1.2	1.6	1.0	1.0	0.4	0.3	0.7	0.8	3.3	3.7
					g ha^{-1} yr^{-1}					
B	199.5	245.9	231.8	187.2	24.1	30.4	37.5$^{\mathbf{a}}$	64.7$^{\mathbf{b}}$	493.0	528.3
Na	652.7	743.5	425.2	396.2	94.5	191.6	85.3$^{\mathbf{a}}$	174.7$^{\mathbf{b}}$	1257.8	1505.9
Zn	409.2	370.7	174.1	145.1	67.6	93.0	86.1	120.2	737.1	729.1
Co	62.0	61.0	7.3	9.0	2.1	3.3	5.0	9.9	76.3	83.1
Cu	29.4$^{\mathbf{a}}$	39.7$^{\mathbf{b}}$	50.6	38.5	14.7	15.4	22.4	25.7	117.2	119.2
Ni	14.5	10.0	2.5	1.6	0.7	0.8	1.2	1.8	18.9	14.1
Mo	0.8$^{\mathbf{a}}$	1.3$^{\mathbf{b}}$	0.9	1.0	0.2	0.3	0.4	0.5	2.3	3.2

4.4 Discussion

4.4.1 Litterfall characteristics and the effect of land management type on litterfall and nutrient deposition

The results showed that annual litterfall and nutrient deposition were independent of farm management type but significant variations in fractional litterfall and nutrient return exists between farm types, which is in line with findings from agroforestry systems in Brazil and India (Fontes *et al*., 2014; Nesper *et al*., 2019). Specifically, Fontes *et al.* (2014) found no significant differences in litterfall between fertilized and unfertilized cocoa agroforests (means of 9.9 and 9.9 Mg ha^{-1} yr^{-1}, respectively) in southern Bahia, Brazil and Nesper *et al.* (2019) also reported similar litterfall in organic and conventional coffee agroforestry systems (Org. 5.7 ± 0.5 vs. Con. 5.0 ± 0.5 Mg ha^{-1} yr^{-1}) in Western Ghats, India. The total annual litterfall on both organic and conventional cocoa farms were within the range (5.0 ± 0.4 – 10.4 ± 0.6) reported for cocoa agroforests in the Ashanti region of Ghana (Dawoe *et al.*, 2010). Similar amounts of annual litterfall have also been reported for agroforests and forests ecosystems in Tanzania (Becker *et al.,* 2015), Indonesia (Triadiati *et al.*, 2011), Central Africa (Averti and Dominique, 2011) and Bangladesh (Hasanuzzaman and Mahmood, 2014). The annual litterfall results reported in this study for both organic and conventional cocoa systems are higher than the values (3.3 – 7.0 Mg ha^{-1} yr^{-1}) reported for most tropical and temperate forests (Zhang *et al.,* 2014), secondary mixed forests (4.2 ± 0.2 Mg ha^{-1} yr^{-1}) in Thailand (Podong *et al.*, 2013) and cocoa and cola plantations (4.7 – 7.3 Mg ha^{-1} yr^{-1}) in Nigeria (Muoghalu and Odiwe, 2011). These differences in mean annual litterfall production is possibly due to differences in tree species composition and diversity, plantation age, canopy cover and soil characteristics (Kumar, 2008; Averti and Dominique, 2011; Triadiati *et al.*, 2011).

The annual leaf litterfall on organic farms (9.8 Mg ha^{-1} yr^{-1}, 79 % of total annual litter) and conventional farms (9.0 Mg ha^{-1} yr^{-1}, 71 % of total annual litter) are consistent with and fall within the commonly reported range of 60 - 90% as the leaf litter portion of annual litterfall for most tropical forests and agroforestry systems (Hasanuzzaman and Mahmood, 2014; Becker *et al.,* 2015). The values for leaf litter portion are, however, lower than the range (96 – 99 %) reported as leaf litter portion for forest systems in Central Africa (Averti and Dominique, 2011). The amount of litterfall in an ecosystem is dependent on stand characteristics and environmental factors and their interaction (Triadiati *et al.*, 2011; Averti and Dominique, 2011; Hasanuzzaman and Mahmood, 2014). The organic and conventional farms evaluated in the present study had similar plantation age, cocoa tree basal area, and shade and total tree densities. Moreover, although organic farms maintained more fruit plants (e.g. *Musa spp.*), litter from these were not accounted for by the litter traps as they were manually removed by farmers. The recommended rate of synthetic fertilizer application on conventional cocoa farms in Ghana is 375 kg ha^{-1} of “Asaase wura”

(0-22-18+ 9Ca+7S+6MgO) and 125 kg ha^{-1} of *Nitrabor* (15.4% N + 25.9% CaO + 0.3% B) (African Cocoa Initiative, 2012; Djokoto *et al.*, 2016). The fact that the organic cocoa systems returned both macro- and micro-nutrients via litterfall similar to that of the conventional farms which were receiving chemical fertilizers suggest their potential to efficiently recycle nutrients which is critical for sustainable cocoa production.

4.4.2 The role of shade tree species in nutrient deposition dynamics

The contribution of shade tree species to leaf litterfall on organic (5.0 Mg ha^{-1} yr^{-1}) farms was similar to the value (5.8 Mg ha^{-1} yr^{-1}) reported by Mamani-Pati *et al.* (2012) on organic coffee systems in Bolivia. Compared to Ofori-Frimpong *et al.* (2007) who reported a range of 1-2 Mg ha^{-1} yr^{-1} as the amount of shade tree species litter in cocoa systems, the values provided in the present study are higher. The fact that annual shade tree species litterfall was positively correlated with canopy cover, tree density, shade species basal area, total basal area and shade tree species richness and diversity (Table 4.4), suggests that these factors influenced annual shade tree litterfall production in the cocoa farms (Kumar, 2008). Thus, the greater deposition of shade tree species leaf litter in organic systems than the conventional systems is attributable to these factors (Chapter 2, Page 38-47).

Whereas both monthly macro- and micro-nutrients stock were significantly associated with only the cocoa leaf litter fraction on conventional farms, they were significantly related to both shade and cocoa leaf litter fractions in the organic systems (Table 4.3), suggesting that cocoa leaf litter is a major source of these nutrients on conventional farms whilst both cocoa and shade tree leaves are the major sources in the organic systems. This is confirmed by the fact that shade tree leaf litter accounted for 30-47 % of annual macro- and micro-nutrient deposition (except Ni, Zn and Co) in organic cocoa systems versus 20-35 % in conventional cocoa systems (Table 4.5). Therefore, the hypothesis of the present study which was that litterfall from shade tree species and their contribution to annual nutrient deposition would be greater on organic systems than conventional systems is supported by the results. Similarly, Fontes *et al.* (2014) reported higher nutrient quality in shade tree species leaves than cocoa and concluded that leaves of shade tree species served as a source of nutrients while cocoa tree leaves functioned predominantly as a sink. In an earlier study (Chapter 2, Page 38-47), food and fruit species (e.g. *Musa sapientum* L. f. thomsonii King ex Baker, *Magnifera indica* L., *Persea americana* Mill. and *Musa paradisiaca* L. Terminalia ivorensis (A. Chev.)) and pioneer tree species (e.g. *Ficus sur* Forssk, *Milicia regia* (A.Chev.) Berg, *Morinda lucida* Benth., *Alstonia boonei* De Wild. and *Holarrhena floribunda* (G. Don) Dur and Schinz) dominated both organic and conventional cocoa systems at Suhum, Ghana. This suggests that pioneer tree species as well as food and fruit species play a critical role in nutrient deposition via litterfall in the studied systems, thus their integration in cocoa systems will contribute to nutrient recycling.

4.4.3 The effect of seasonality on nutrient deposition via litter fall

Seasonality affected the pattern and amount of litterfall (Figure 4.1) as postulated. For example, the largest monthly litterfall contributed 2-3-fold the contribution of the lowest monthly litterfall on both farm types. Several studies have demonstrated that litter fall in cocoa agroforests and tropical forests follow a seasonal pattern (Dawoe *et al.*, 2010; Triadiati *et al.*, 2011; Podong *et al.*, 2013; Zhang *et al*., 2014; Becker *et al.,* 2015). Triadiati *et al.* (2011) showed that litterfall production was influenced by monthly variations in climatic factors such as temperature, humidity, wind speed and precipitation as well as their interaction. Furthermore, Zhang *et al.* (2014) demonstrated that litter peaks in most temperate and tropical forest types are influenced by precipitation, temperature and solar radiation. The peak litterfall production during the dry season reported in this study is an indication of the trees physiological response to increased temperature and reduced humidity (Zhang *et al.*, 2014). The peaks during the rainy season is as a result of the mechanical action of strong winds and thunderstorms (Dawoe *et al.*, 2010; Nester *et al.,* 2019). Plants shed their leaves during the dry season as an adaptation mechanism to limited water availability (Wang *et al.*, 2008). Tree species may also respond to seasonal changes in soil properties such as pH or salinity thus within-year variations in litterfall in tropical stands may mirror pronounced edaphic cues (Kumar, 2008).

Nutrient deposition via litterfall varied according to season due to differences in litterfall and nutrient concentration (Figures 4.1-4.3). The concentration of nutrients in litter depends on the rate of nutrient resorption, tree species and the age of the leaves (Hartemink, 2005; Kumar, 2008; Nester *et al.*, 2019). Fresh leaves contain greater levels of nutrient contents than old leaves due to minimal nutrient resorption in fresh leaves (Hartemink, 2005; Kumar, 2008). This implies that periods of greater fresh leaves deposition due to mechanical action of strong winds or thunderstorms are likely to show greater levels of nutrient concentration compared to periods where defoliation is due to leaf ageing (Kumar, 2008). The finding of higher nutrient concentrations in monthly litterfall during the rainy season than the dry seasons on both farm types supports this notion (Appendix Figures 1-2) and consequently, the hypothesis of the study. Moreover, different species have different nutrient contents in their litter (Hartemink, 2005; Nester *et al.*, 2019).

In their review, van Vliet *et al*. (2015) suggested that temporal changes in nutrient contents of litter are associated with leaf flushing, cocoa pod production dynamics and light intensity. For example, light intensity, which is regulated by radiation from the sun, tree density and canopy cover, has been shown to be inversely related to the concentrations of N and K and positively associated with Ca in leaf litter whilst having no effect on leaf Mg and P (van Vliet *et al*., 2015; Wessel 1971). The transfer of nutrients to leaves of new flushes or young cocoa pods may lead to decreases in nutrient contents of senesced leaves. Climatic factors moderated by stand characteristics such as shade tree species composition and diversity and canopy cover may also interact with leaf flushing and cocoa fruit bearing to regulate changes in nutrient concentrations and stocks over time in the two systems.

4.5 Conclusion

Litterfall production and nutrient deposition via litterfall followed a temporal pattern with peak deposition in the dry season regardless of farm management type. Overall litterfall production and deposition of macro- and micro-nutrients were similar in both organic and conventional cocoa systems but significant variations in fractional litterfall and nutrient return existed between the two farm types. Shade tree species leaves served as a major source of annual litterfall and nutrient deposition, indicating a complementary role of the different shade tree species which are maintained in both cocoa systems but more so in the organic systems than the conventional farms. It was concluded that organic management of cocoa agroforestry systems ensure nutrient return similar to those receiving synthetic fertilizers, and that leaf litter from shade trees is a critical mechanism by which nutrients are returned to the soil in organic cocoa systems.

5 DECOMPOSITION AND NUTRIENT MINERALIZATION OF LEAF LITTER IN SMALLHOLDER COCOA AGROFORESTS: A COMPARISON OF ORGANIC AND CONVENTIONAL FARMS IN GHANA

Abstract

Smallholder cocoa farmers rely heavily on natural nutrient recycling to maintain soil fertility in their farms. Decomposition of deposited litter is an essential process which makes nutrients available for uptake by vegetation. Although litter decomposition and nutrient release patterns have been studied in cocoa agroforestry systems in general, studies focusing on organic and conventional cocoa systems are lacking which is critical as organic farms are particularly dependent on nutrient returns from decomposing litter. Leaf litter decomposition and the mineralization of macro and micro-nutrients were studied in organic and conventional cocoa agroforestry systems using the litterbag technique for 12 months. Initially rapid and subsequently slower decomposition of leaf litter was found on both farm types. The average monthly mass loss was 9.2 - 14.4 g month^{-1} on organic farms and 4.2 - 7.3 g month^{-1} on conventional farms in the first five months. The annual rate of decomposition (k) was higher on organic farms (1.9) compared to conventional systems (1.3). The time required for 50% (t_{50}) and 99% (t_{99}) decomposition of leaf litter were both lower on organic farms (t_{50} = 0.4 years, t_{99} = 2.6 years) than conventional farms (t_{50} = 0.5 years, t_{99} = 3.9 years). Macro-nutrients (N, P, K, S, Mg and Ca) were released in the order K > S > N = Mg > P > Ca on organic farms and the estimated k values for these nutrients were 41-89% higher on organic farms compared to conventional systems. Similarly, the estimated k values for micro-nutrients were 39-81% greater on

organic than conventional cocoa farms. The study demonstrates that organic management of cocoa agroforestry systems enhances leaf litter decomposition and nutrient mineralization and that organic management contributes to the sustainability of soil fertility in smallholder cocoa agroforestry systems.

5.1 Introduction

Cocoa production is worth over 12 billion US$ and provides livelihoods for 40-50 million people worldwide (Hütz-Adams *et al.*, 2016). As the backbone of Ghana's economy, cocoa production serves as the primary source of livelihood for 25-30% of Ghanaians (Kaba, 2017). Although there is a growing demand for cocoa, its production is at cross-roads due to depletion of soil nutrients (ICCO, 2014; Hütz-Adams *et al.*, 2016; Kaba, 2017). Depletion of soil nutrients and organic matter is a serious threat to sustaining cocoa production in West Africa and elsewhere (Daymond *et al.*, 2017; Kaba, 2017). Dwindling soil nutrients limit cocoa production in major cocoa producing countries (Daymond *et al.*, 2017; Kaba, 2017; Hütz-Adams *et al.*, 2016).

Litter inputs from vegetation is a major pathway by which nutrients are returned to soils (Triadiati *et al.*, 2011; Naik *et al.*, 2018). Plant litter improves soil organic matter quality and quantity which in turn enhances soil quality through reducing bulk density and erosion, enhancing soil structure, increasing cation-exchange capacity, infiltration, water holding capacity, and the retention of soil nutrients (Murphy, 2014; Bünemann *et al.,* 2018). Additionally, plant litter enhances biodiversity and activity of soil microorganisms which underpins plant productivity (Barrios *et al.*, 2018). Plant litterfall therefore plays a critical role in determining the physical, chemical and biological characteristics of soil as well as the productivity of an ecosystem.

Litter in general and leaf litter in particular is a central nutrient resource and litterfall is a critical link between plants and soils for the return and recycling of organic matter and nutrients (Hartemink, 2005; Triadiati *et al.*, 2011; Van Vliet *et al.*, 2015; Naik *et al.*, 2018), maintenance of soil fertility and ultimately contributes to the regulation of primary productivity in an ecosystem (Mamani-Pati *et al.,* 2012; Fontes *et al.*, 2014).

The transfer of nutrients between the living and non-living components of an ecosystem is important to ensure its stability. Decomposition of deposited litter make nutrients available for uptake by vegetation. The rate at which litter accumulates on the floor of an ecosystem is dependent on biotic and abiotic factors such as species composition and structure, age of the vegetation or plantation, composition and activities of decomposers, climate and land use (Dawoe *et al.,* 2010; Mamani-Pati *et al.,* 2012; Fontes *et al.*, 2014), all of which are affected by management type. Decomposition is a complex process that ultimately reduces dead organic matter or litter into constituent mineral nutrients, water and carbon dioxide (Dawoe *et al.,* 2010; Kaba, 2017). The rate of litter decomposition in an ecosystem depends on the interaction of a variety of factors such as litter quantity and quality (e.g concentration of nitrogen, phosphorus, lignin, polyphenols and their ratios), variety, composition and activities of decomposers, climatic conditions (particularly temperature and humidity), soil nutrient content and availability, and type of vegetation (Dawoe *et al.,* 2010;

Triadiati *et al.*, 2011; Naik *et al.*, 2018; Kaba, 2017; Hasanuzzaman and Mahmood, 2014).

Cocoa agroforestry is the practice of growing cocoa under a variety of shade species together with food crops (Dawoe *et al.*, 2010; Somarriba *et al.*, 2013). The integration of trees into cocoa farms and its subsequent management can counteract the reduction of nutrient and organic matter content in soils through litter inputs from the shade species (Mamani-Pati *et al.,* 2012; Fontes *et al.*, 2014). Cocoa is generally grown under shade in Ghana and is either organically or conventionally managed. Conventional cocoa systems rely on synthetic agrochemicals for nutrient replenishment and weed and pest control whilst the organic farms rely on organic products as well as natural processes to supplement soil nutrients and control weeds and pests. Synthetic agrochemical-dependent cocoa systems pose threats to soil, animal and human health (Barrios *et al.*, 2015) and their sustainability in the long-run is questionable. Moreover, the use of synthetic agrochemicals can modify litter-soil biota and pose a threat to the decomposition processes.

In Ghana, it is common to remove shade trees in conventionally managed farms driven by the desire to increase short term yield (Asare *et al*., 2014; Dawoe *et al.*, 2016; Benefoh, 2018). Removal of shade trees pushes cocoa systems closer to monocultures thus reducing litter inputs from shade species. Because organic farming disallows the use of synthetic fertilizers, farmers opt to maintain shade species in their cocoa farms as a means to supplement soil organic matter and nutrients, reduce nutrient leakage and increase soil quality.

According to Naik *et al.* (2018) and Kaba (2017), the rate of organic matter decomposition is critical to the functionality of any agroforestry system. Although litter and nutrient decomposition has been studied in cocoa agroforestry systems in general, studies focusing on organic and conventional cocoa systems are rare. In agroforestry systems, nutrient supply rate and nutrient limitation are closely linked via management (Kumar, 2008; Ofori-Frimpong *et al.,* 2007; Mamani-Pati *et al.*, 2012). Smallholder cocoa farmers rely heavily on natural nutrient recycling for soil fertility sustenance in their farms, it is therefore important to understand the dynamics of litter and nutrient decomposition in organic and conventional cocoa systems as this will contribute to efficient management of these systems. The present study quantified and compared the rate of litter decomposition and nutrient mineralization on organic and conventional cocoa agroforestry systems. It was hypothesized that organic management of cocoa systems would result in greater rate of litter decomposition and nutrient return to the soil than conventional management due to greater moisture content and improved conditions (e.g. non-use of synthetic agrochemicals, ameliorated micro-climatic conditions and great variety of litter inputs) of the decomposer communities.

5.2 Methods

5.2.1 Description of study site

This study was conducted in two cocoa communities (Nsuta-wawase and Kuano) in Suhum Municipality, Eastern Region, Ghana (Figure 2.1). Detail description of the study area has been presented in Chapter 2 (Page 27-30). The climate is tropical with a mean annual temperature and precipitation of 24-29° C and 12270-1651 mm respectively (Figure 5.1). Both the organic and conventional cocoa are produced under shade and details of the two systems in terms of species composition, yield and other biophysical characteristics are found in Chapter 2 (Page 30-47).

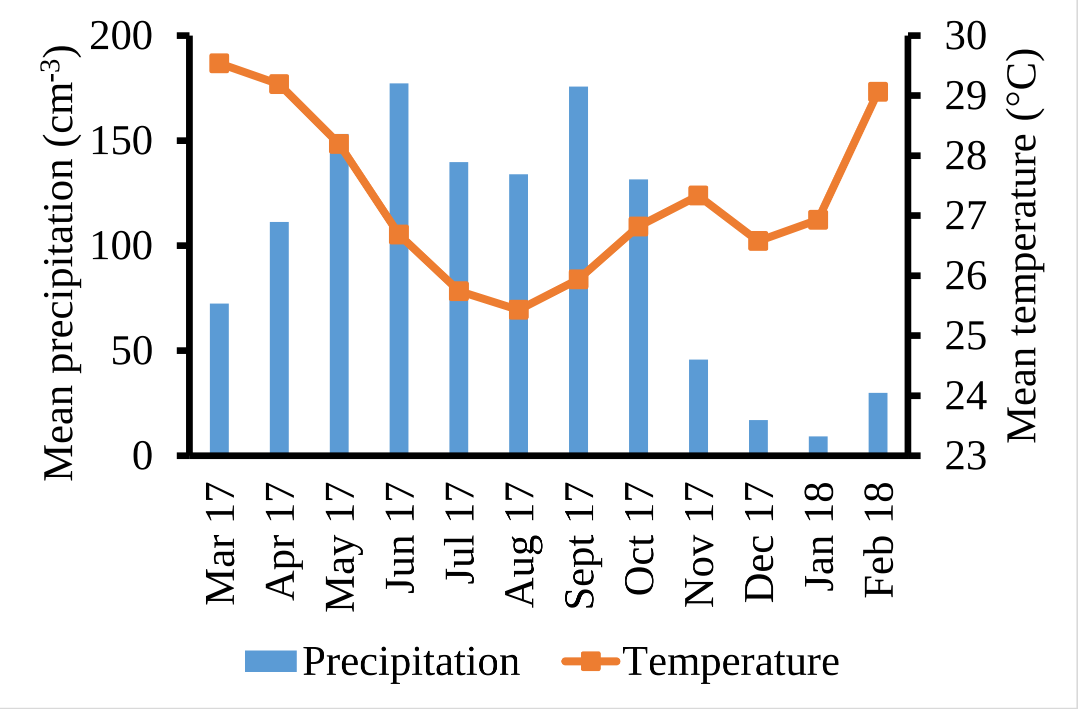

Figure 5.1: Long term mean monthly precipitation and temperature (1901 to 2018; World Bank Group, 2018 and Web 2).

5.2.2 Selection of cocoa farms

We randomly selected two cocoa villages from a list of organic and conventional cocoa producing areas (provided by COCOBOD, the regulator of the sector) in the Suhum Municipality of the Eastern Region of Ghana. Eight organic and eight conventional farms were randomly selected from separate lists of farmers involved in cocoa production in the two selected cocoa communities and 25 m x 25 m plots were established on their farms (e.g. Muoghalu and Odiwe, 2011). Fieldwork was conducted in private farms and the selected farmers orally consented to participate in the research. The age of the cocoa trees on the selected farms ranged from 15-30 years.

5.2.3 Sample collecting and processing

The experiment was conducted using the litterbag technique over a 12-month period. Bulks of freshly fallen cocoa and shade tree leaf litter were collected from the floor of the selected cocoa farms in January 2017 (e.g. Muoghalu and Odiwe, 2011; Hayashi *et al*., 2012). Leaf litter was air-dried for three days and thoroughly mixed (e.g. Muoghalu and Odiwe, 2011; Naik *et al*., 2018). Seventy grams of leaf litter from each farm was placed into 30 cm x 20 cm nylon netting litterbags with 2 mm mesh size (e.g. Hayashi *et al*., 2012; Naik *et al*., 2018). Thirty-six litterbags were placed on each farm and three bags from each farm were oven dried at 70º C for initial litter chemistry analysis (e.g Naik *et al*., 2018). Three bags from each farm were subsequently retrieved monthly throughout the experimental period. Collected samples were gently and briefly washed under slowly running tap water, rinsed with distilled water, oven-dried for 48 hours at 70 ºC and weighed to determine mass loss (e.g Naik *et al*., 2018). Litter decomposition and nutrient mineralisation rates were expressed as loss of dry matter (DM) and percentage nutrient release per month (% mon^{-1}) respectively.

5.2.4 Chemical analysis

Oven-dried samples were milled using an agate ball mill (Retch PM 400) at 290 rpm for 15 minutes and analysed for their chemical composition. Total C and N contents in the milled samples were obtained using CN analyser (Thermo Scientific™ Flash™ 2000 Organic Elemental Analyzer (OEA)). To determine the proportion of C and N, 5-6 mg of milled samples were combusted at 900 °C to produce nitrogen oxides, carbon dioxide and water which were eluted and detected. Six ml of concentrated NHO_3 was added to 0.2 g of powered samples, microwave-digested and analysed for macro- and micro-nutrients using ICP-MS (Thermo Scientific™ iCAP™ TQ). Chemical analysis for macro- and micro-nutrients were conducted every month, except C and N which were conducted every three months.

5.2.5 Data analysis

Annual leaf litter decay constants were estimated through regression analyses (Olsen, 1963) using SigmaPlot (vs. 13). Decay constants of organic matter, macro and micro-nutrients were obtained by using the model $m = Ae^{-kt}$, where m is the % initial dry mass or nutrient remaining at time t, A is a constant, k is the coefficient of the rate of decay *per* year, and t is the time in years. The amount of nutrients remaining was estimated as NR (%) = $(C_t \times M_t/I_n \times I_m) \times 100$, where NR = remaining nutrients (%), C_t = nutrient concentration at time t (mg/kg), M_t = oven-dry mass at time t (g), I_n = initial nutrient concentration (mg/kg) and I_m = initial oven-dry mass (g). The time required for 50 % (t_{50}) and 99 % (t_{99}) decomposition of leaf litter and nutrients were computed as $t_{50} = 0.693/k$ and $t_{99} = 5/k$ (Olsen, 1963; Naik *et al.*, 2018).

The test for normality for each variable was conducted using the Shapiro-Wilks W-test for homogeneity of variances; variables with variances which were not normally distributed were Box-Cox transformed. One-way ANOVA was used to assess mean differences in initial litter chemistry and repeated measures ANOVA was used to establish differences in mean values of nutrient remaining; *p*-values < 0.05 were considered significant. The repeated measures ANOVA analysis was restricted to the first 10 months of leaf litter installation because decomposition on organic farms was completed during this period. Where interaction terms were not significant, only main effects were considered in results and discussion.

5.3 Results

5.3.1 Initial litter nutrient content from organic and conventional farms

Leaf litter from organic farms were 20, 49 and 63 % higher in S ($F_{1, 14}$ = 13.20, *p* = 0.003), Fe ($F_{1, 14}$ = 4.75, *p* = 0.047) and Al ($F_{1, 14}$ = 13.14, *p* = 0.003) respectively compared to conventional farms. The initial mean values for other plant macro- and micro-nutrients as well as the litter C to N ratio (Table 5.1) were similar between organic and conventional farms.

Table 5.1 Macro and Micro-nutrients concentrations (Mean± SEM) of leaf litter from organic and conventional cocoa farms in Suhum Municipality, Ghana. Columns with different letters indicate significant differences (*p* <0.05) and those with without letters were similar.

		Farm type	
Parameter	**Nutrient**	**Organic**	**Conventional**
Primary macro-nutrients	C (%)	40.61 ± 0.76	40.59 ± 0.48
	N (%)	1.23 ± 0.09	1.38 ± 0.11
	P (g kg^{-1})	1.50 ± 0.56	1.37 ± 0.22
	K (g kg^{-1})	8.54 ± 0.56	9.36 ± 1.33
Secondary macro-nutrients	Mg (g kg^{-1})	2.77 ± 0.10	2.94 ± 0.12
	Ca (g kg^{-1})	14.03 ± 0.54	15.53 ± 0.65
	S (g kg^{-1})	1.78 ± 0.07$^{\mathbf{a}}$	1.48 ± 0.03$^{\mathbf{b}}$
Micro-nutrients	Na (g kg^{-1})	0.20 ± 0.03	0.17 ± 0.01
	Al (g kg^{-1})	0.93 ± 0.08 $^{\mathbf{a}}$	0.57 ± 0.05 $^{\mathbf{b}}$
	Mn (g kg^{-1})	0.87 ± 0.09	0.67 ± 0.06
	Fe (g kg^{-1})	0.73 ± 0.09 $^{\mathbf{a}}$	0.49 ± 0.10 $^{\mathbf{b}}$
	B (mg kg^{-1})	37.51 ± 1.95	38.6 ± 1.91
	Co (mg kg^{-1})	21.48 ± 2.85	21.02 ± 5.64
	Ni (mg kg^{-1})	1.11 ± 0.21	0.76 ± 0.12
	Cu (mg kg^{-1})	20.59 ± 2.08	20.62 ± 4.38
	Zn (mg kg^{-1})	53.94 ± 13.71	32.13 ± 3.38
	Mo (mg kg^{-1})	0.39 ± 0.06	0.43 ± 0.10
C/N		33.67 ± 1.83	30.05 ± 1.96

5.3.2 Mass loss of leaf litter on organic and conventional cocoa farms

The decomposition of leaf litter expressed as loss of dry matter (DM) followed a similar pattern on both farm types but was more rapid on organic farms than conventional farms (Figure 5.2). Compared to conventional farms, the average mass loss *per* month on organic farms was greater by up to 300% in the second and third months (March and April 2017), 200% from the fourth to sixth month (May-July 2017) and 20-50 % from the seventh to tenth month (August-November 2017). The annual rate of decomposition (k) was 47 % greater on organic farms than conventional farms (Table 5.2). The time required for 50% (t_{50}) and 99% (t_{99}) decomposition of leaf litter on organic farms were both 47% lower than on conventional farms.

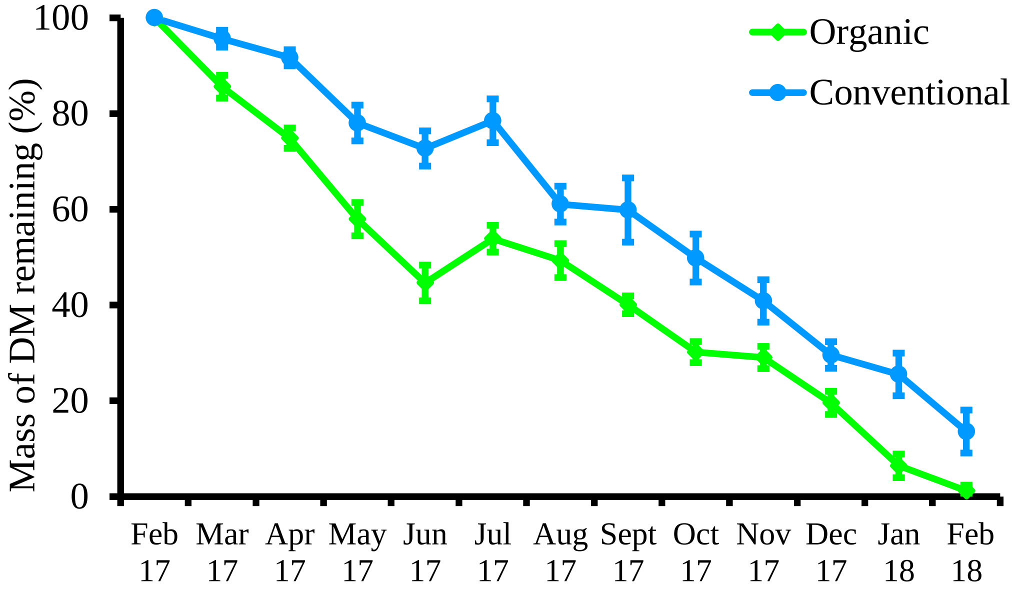

Figure 5.2 Changes in mass remaining (%) over 12 months comparing organic and conventional farms at Suhum. Means ± SE are shown. DM is dry matter.

Table 5.2 Annual decomposition constant (k), decay time for 50 and 99 % of mass and nutrients for leaf litter from organic and conventional farms at Suhum.

	Organic				**Conventional**			
Parameter	**K**	**t_{50}**	**t_{99}**	**R^2 (%)**	**K**	**t_{50}**	**t_{99}**	**R^2 (%)**
Dry matter	1.90	0.36	2.63	88	1.30	0.53	3.86	79
N	2.65	0.26	1.89	93	1.88	0.37	2.66	88
P	2.61	0.27	1.91	79	1.73	0.40	2.88	71
K	4.22	0.16	1.19	92	2.72	0.25	1.84	89
Mg	2.65	0.26	1.89	93	1.67	0.42	3.00	85
Ca	2.25	0.31	2.22	90	1.54	0.45	3.25	82
S	3.36	0.21	1.49	93	1.77	0.39	2.82	84
Na	3.14	0.22	1.59	83	1.74	0.40	2.88	74
Al	3.54	0.20	1.41	93	2.44	0.28	2.05	81
Mn	2.83	0.24	1.77	91	1.87	0.37	2.68	82
Fe	3.84	0.18	1.30	95	2.61	0.27	1.92	78
B	3.08	0.22	1.62	91	1.84	0.38	2.72	86
Co	2.91	0.24	1.72	89	1.94	0.36	2.58	69
Ni	2.81	0.25	1.78	92	1.93	0.36	2.59	75
Cu	2.73	0.25	1.83	91	1.96	0.35	2.55	82
Zn	3.03	0.23	1.65	83	1.93	0.36	2.60	79
Mo	2.90	0.24	1.73	85	1.94	0.36	2.58	67

5.3.3 Macro-nutrients release dynamics

On both organic and conventional farms, the release of N in leaf litter followed the same pattern but the average release *per* month was 30, 20 and 9 % greater in the third, sixth and ninth months, respectively, on organic compared to conventional systems (Figure 5.3a-f; Table 3). At the end of the first three months of decomposition, more than 40% of the N-content in leaf litter from both organic and conventional farms was released. The annual mineralisation constant (k) was 41% greater on organic farms than conventional farms (Table 2). The t_{50} and t_{99} values for organic cocoa farms were 41% lower than conventional farms.

Primary (P and K) and secondary (S, Ca and Mg) macro-nutrients in leaf litter on organic farms were rapidly mineralized from the first to fourth months, with the most rapid mineralization for K followed by S, P, Mg and Ca. Thereafter these nutrients were gradually released over the rest of the experimental period (Figure 5.3). Nutrient release was consistently higher on organic farms than conventional farms (Figure 5.3; Table 5.3). On conventional farms, the mineralization of these nutrients was gradual from the first to the twelfth month, except P which showed a rapid decrease in the first month. While the annual decomposition rate constant for P, K, Mg and Ca on organic farms was 47-59 % higher than conventional farms, it was 89% higher for S (Table 5.2). On organic farms, estimated t_{50} and t_{99} values for P, K, S, Mg and Ca were consistently 47-89 % lower than conventional systems.

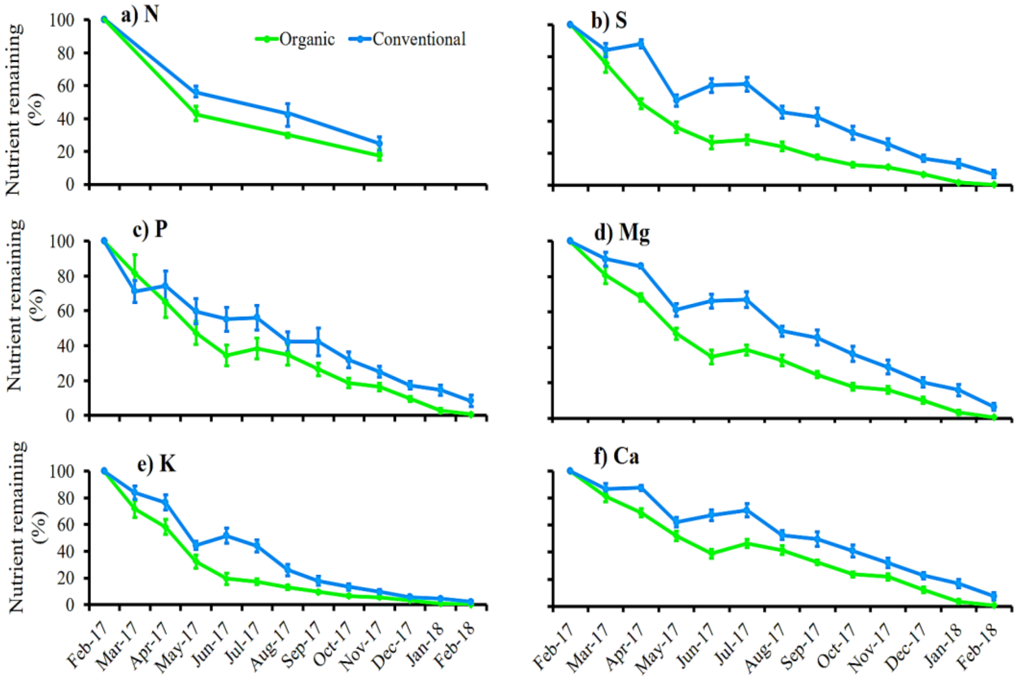

Figure 5.3 Decay pattern of macro-nutrients (panels a-f, Mean ± SEM) of leaf litter on organic and conventional cocoa farms at Suhum.

Table 5.3 Repeated measures ANOVA of mass and macro-nutrient remaining (%) versus farm type and month. ‘a’ degrees of freedom is $F_{1\ 14}$ for all parameters except C and N ($F_{1\ 10}$); ‘b’ degrees of freedom is $F_{9\ 126}$ for all parameters except C and N ($F_{3\ 30}$). P-values are in parenthesis and are significant for $p < 0.05$.

Parameter	**Mass/Nutrient remaining (%)**	**F-value**		
		Farm type^{a}	**Month**^{b}	**Farm type x Month**^{b}
Dry matter	Mass	27.61 (< 0.001)	116.26 (< 0.001)	2.65 (0.023)
Primary macro-nutrients	C	11.34 (0.007)	168.23 (< 0.001)	6.07 (0.010)
	N	6.38 (< 0.030)	211.68 (< 0.001)	1.71 (0.194)
	P	2.36 (0.147)	81.21 (< 0.001)	2.69 (0.039)
	K	16.38 (0.001)	200.23 (< 0.001)	5.75 (< 0.001)
Secondary macro-nutrients	Mg	34.01 (< 0.001)	155.19 (< 0.001)	3.67 (0.007)
	Ca	20.17 (< 0.001)	138.88 (< 0.001)	4.00 (0.002)
	S	38.10 (< 0.001)	160.98 (< 0.001)	9.59 (< 0.001)

5.3.4 Micro-nutrients release dynamics

The mineralization of micro-nutrients was significantly higher on organic farms than conventional farms (Figure 5.4a-j; Table 4). Specifically, from the first to the fourth month of decomposition, the micro-nutrients Fe, Mo, B, Cu, Mn, Na, Zn, Ni, Co and Al were rapidly released on organic farms and then gradually released from the sixth to the twelfth month (Fig 5.4a-j). On conventional farms, the aforementioned micro-nutrients were generally gradually released from the first month to the twelfth month, except during the third month where nutrient release was rapid for Fe, Zn, Al, Ni, Mn and Mo. The concentration of Ni, Al and Co relatively increased in the remaining substrate in the fifth month on organic farms.

On conventional farms, whereas increase in the concentration of Fe ($F_{1, 14} = 7.67$, $p = 0.015$) occurred during the fifth month, it occurred during the fourth and fifth months for Zn ($F_{1, 14} = 10.78$, $p = 0.005$). Whiles the annual k values for Cu was 39 % greater on organic farms than conventional farms, it was 45-68 % greater for Al, Mn, Fe, Co, Zn, Mo and B, and 81 % higher for Na (Table 5.2). The t_{50} and t_{99} values of the aforementioned micro-nutrients were 39-81 % lower on organic farms compared to conventional farms. Micro-nutrients were released in the order Fe > Al > Na > B > Zn > Co > Mo > Mn > Ni > Cu on organic farms and in the order Fe > Al > Cu > Co > Mo > Ni > Zn > Mn > B > Na on conventional farms.

Table 5.4 Repeated measures ANOVA of micro-nutrient remaining (%) versus farm type and month. 'a' degrees of freedom is $F_{1\ 14}$ for all parameters; 'b' degrees of freedom is $F_{9\ 126}$ for all parameters. P-values are in parenthesis and are significant for $p < 0.05$.

Micro-nutrient remaining (%)	**F-value**		
	Farm type[a]	**Month[b]**	**Farm type x Month**
Na	11.67 (0.004)	100.83 (< 0.001)	3.98 (0.009)
Al	13.05 (0.003)	156.96 (< 0.001)	4.99 (0.001)
Mn	26.42 (< 0.001)	109.43 (< 0.001)	3.26 (0.013)
Fe	10.40 (0.006)	158.79 (< 0.001)	4.80 (0.002)
B	27.83 (< 0.001)	173.14 (< 0.001)	4.07 (0.003)
Co	4.77 (0.047)	95.53 (< 0.001)	4.09 (0.007)
Ni	5.93 (0.029)	114.21 (< 0.001)	3.54 (0.016)
Cu	9.16 (0.009)	149.48 (< 0.001)	3.02 (0.018)
Zn	7.70 (0.015)	89.21 (< 0.001)	4.79 (0.005)
Mo	4.10 (0.062)	122.50 (< 0.001)	3.19 (0.035)

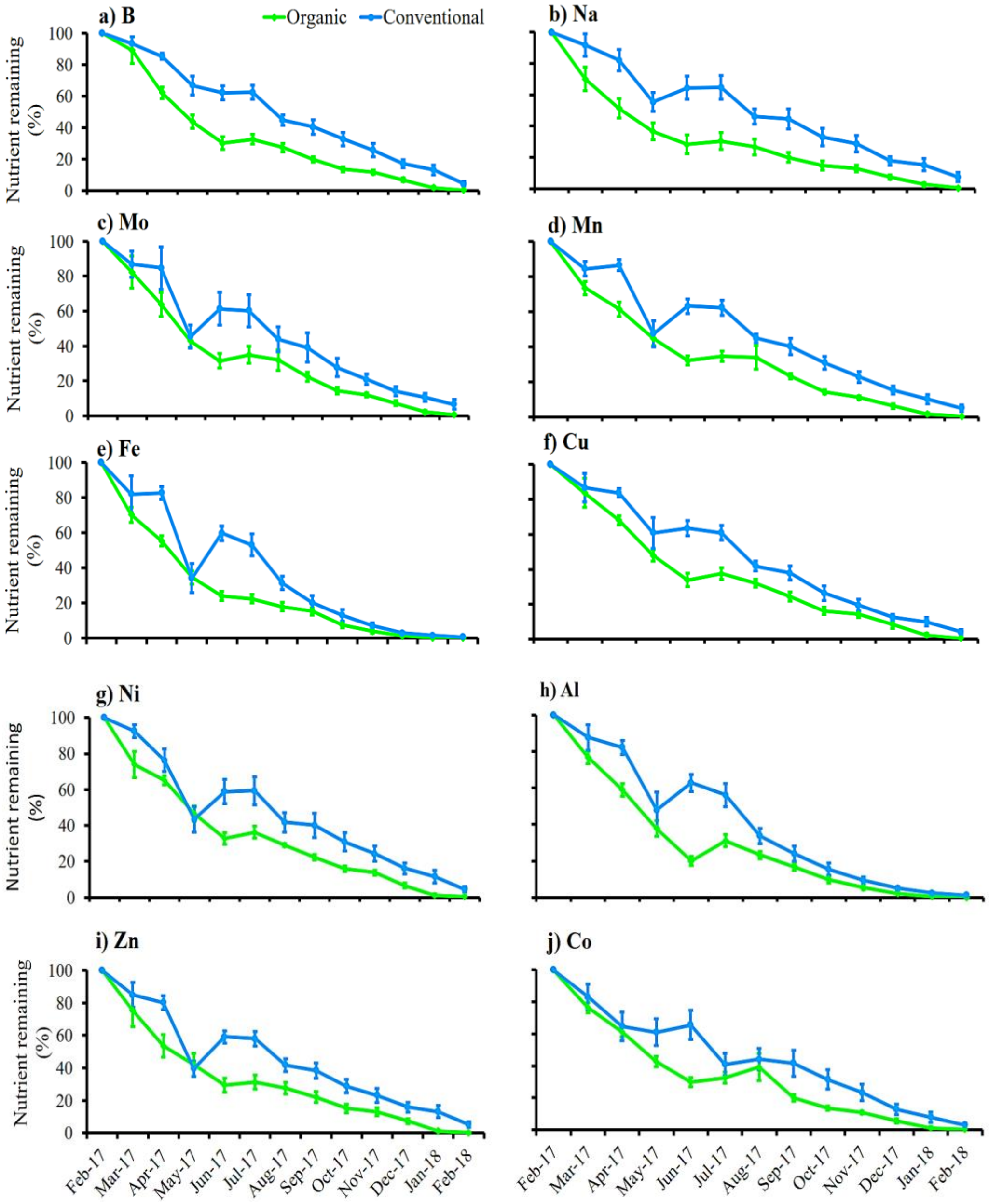

Figure 5.4 Decay pattern of micro-nutrients (panels a-j, Mean ± SEM) in leaf litter on organic and conventional farms over 12 months at Suhum.

5.4 Discussion

5.4.1 Initial litter chemistry

Initial litter quality on both organic and conventional cocoa farms are comparable to and fall within the values reported by Kaba (2017) in Ghana and Rojas *et al.* (2017) in Colombia. The greater levels of S (20 %), Fe (49 %) and Al (63 %) in leaf litter on organic farms compared to conventional farms is likely because organic farms maintained greater shade tree species diversity (Chapter 2, Page 38-47), and that leaf litter inputs from these trees accounted for the observed differences (Chapter 4, Page 111-115). Fontes *et al.* (2014) found that cocoa leaves served as a sink for nutrients while shade tree leaves served as a source. Moreover, Wood *et al.* (2006) asserted that for non-limiting nutrients such as Fe and Al, there is a large degree of plant control over the amount of soluble nutrients that are resorbed before leaf abscission. The C to N ratios reported in this study for both farm types are similar to the ratio of 31.6 ± 2.7 reported for 30-year old cocoa systems but lower than the 42.9 ± 1.5 reported for 15-year old cocoa systems by Dawoe *et al.* (2010). The high C/N ratio (> 25) suggests that decomposition on both farms was partly regulated by leaf-litter chemistry.

5.4.2 Litter decomposition

The present study found an initial phase of rapid mass loss followed by slower phase, a pattern reported in several other studies (Kumar, 2008; Ofori-Frimpong, 2007; Kaba, 2017; Rojas *et al.*, 2017; Naik *et al.*, 2018). The initial rapid mass loss is attributable to the leaching and breakdown of readily soluble substances, non-lignified carbohydrates and other labile fractions as reported in other studies (Isaac and Nair, 2005; Kumar 2008; Triadiati *et al*, 2011; Dawoe *et al.*, 2010). The assertion that 30-50% of leaf biomass decomposes in the first 3-4 months in tropical agroforestry and plantation systems (Kumar, 2008) was supported by this study as more than 30 % of leaf biomass was lost within this period (Figure 5.2).

The more gradual mass loss in the latter stages is likely linked to the accumulation of recalcitrant fractions such as cellulose, lignin, waxes and tannin in leaf litter (Naik *et al.*, 2018; Fontes *et al.,* 2014; Kumar, 2008). Moreover, leaf litter in cocoa systems are predominantly cocoa leaves which are known to contain higher levels of lignin and polyphenol than forest trees (Dawoe *et al.*, 2010). The rate of decomposition and mineralization of leaf litter in cocoa systems are influenced by litter quality, soil organisms and physical environment (Fontes *et al.*, 2014; Kumar, 2008). Initial litter quality (C/N, C, N, P and K) were similar on both farm types but decomposition occurred at different rates suggesting that extrinsic factors both environmental and biological and their interaction with leaf-litter quality possibly accounted for the differences in decomposition rates on the two farm types (Kumar, 2008).

As it was postulated in the present study, the rate of litter decomposition and nutrient return was greater on organic farms than conventional farms (Figure 5.2; Table 5.2). While the decay rate coefficient (k) reported in this study for organic cocoa agroforestry systems is comparable to Indonesian natural forests during the wet period (k = 1.87, Triadiati *et al*, 2011) and secondary forests in eastern Amazon (k= 1.2-1.9, Hayashi *et al.,* 2012), it is higher than the 0.46-1.11 for cocoa agroforestry systems in Brazil (Fontes *et al.,* 2014), the 0.15 reported for secondary mixed deciduous forests in Northern Thailand (Podong *et al*., 2013) and the 0.35 for secondary forests in the Ashanti region of Ghana (Dawoe *et al.,* 2010). The rapid decomposition in organic systems accelerates nutrient return to the soils, thus enhancing their availability to cocoa and shade trees for growth and productivity. Thus, although the annual litterfall and nutrient deposition via litterfall were similar on both farm types (Chapter 4, Section 4.4.3), the organic farms recycle nutrients more efficiently than the conventional farms.

The greater coefficient of decomposition observed on organic compared to conventional cocoa farms is attributable to possible differences in the composition and activities of decomposer communities (Domínguez *et al.,* 2014; Lori *et al.*, 2017). Microbes play an essential role in nutrient cycling in ecosystems and organic matter is a central source of energy for microbial life (Kumar, 2008). Land management influences the population of soil biota, their activities and effectiveness in nutrient cycling to maximise nutrient availability to plants (Murphy, 2014; Barrios *et al.,* 2015). Agrochemical usage on conventional farms possibly altered decomposer communities thus accounting for lower decomposition and nutrient release rate whereas the general effect of more adapted soil biota and local decomposers enhanced decomposition on the organic farms (Domínguez *et al.,* 2014; Lori *et al.*, 2017; Barrios *et al.*, 2015). Site conditions such as micro-climate, soil moisture and fertility and evapotranspiration reportedly moderate litter decomposition by influencing decomposer biomass, microbial and enzyme activities (Wood *et al.*, 2006; Fontes *et al.*, 2014). High nutrient resorption which characterises plants on nutrient-deficient soils leads to low litter quality and decomposition rates (Wood *et al.*, 2006; Kumar, 2008).

5.4.3 Nutrient release dynamics

The study found greater rate of nutrient release on organic farms than conventional farms; this is in line with previous findings from agricultural systems (Vazquez *et al.* 2003; Domínguez *et al.,* 2014; Fließbach *et al.*, 2000). The chemical structure of leaf litter moderates the release or immobilization of its nutrient contents (Kumar, 2008). For example, soluble P containing compounds are easily leached during decomposition and non-structural elements such as K are rapidly lost from the organic material when the cell wall breaks down during decomposition, thus explains why primary macro-nutrients release in the present study followed the pattern

K>N>P (Table 5.2; Naik *et al.*, 2018; Dawoe *et al.*, 2010; Issac and Nair, 2005; Hossain *et al*., 2011). The decomposition and nutrient mineralization of *Albizia procera* leaf litter reportedly followed the pattern K>N>P in Central Indian agroforestry systems (Gupta *et al.*, 2017). K plays a critical role in the synthesis of carbohydrates hence cocoa trees demand high quantities of it (Chacin *et al.,* 1999), thus its rapid release would make it readily available to support greater cocoa tree growth and production.

Contrary to previous studies (Lin *et al.*, 2007; Hossain *et al*., 2011; Hasanuzzaman and Mahmood, 2014) that reported N or P immobilization, there was no N or P immobilization observed in the present study. The rapid release of secondary macro-nutrients and its release pattern (S>Mg>Ca) reported in this study is similar to Fontes *et al.* (2014) but contrary to the findings of Kaba (2017). The mass loss in leaf litter and increased concentration of some nutrients (Figure 5.3 and 5.4) in the remaining litter material possibly reflects the mineralization of carbon and the immobilization of those nutrients by soil biota (Naik *et al.*, 2018) or atmospheric deposition (Hossain *et al.*, 2011). Moreover, Lin *et al.* (2007) stated that leaf litter serves as a surface for fungi or heterotrophic organisms. The subsequent release of nutrients in the residual material after the period of immobilization may be attributed to microbial oxidation of recalcitrant litter components and physical-biological fragmentation (Naik *et al.*, 2018; Gupta *et al.*, 2017). Different species have different nutrient release patterns, which are attributable to an interaction between litter quality and seasonal environmental factors (Hartemink, 2005; Lori *et al.,* 2017; Gupta *et al.,* 2017). Furthermore, litter chemistry changes over time as decomposition progresses, thus continuously affecting the rate of substrate decomposition and nutrient mineralization (Kumar, 2008; Domínguez *et al*., 2014; Lori *et al.,* 2017).

5.5 Conclusion

The findings showed that mass loss and nutrient release follow the same pattern on both organic and conventional cocoa farms, but at a faster rate on organic farms. Litter was more readily decomposed, and nutrients were more available (i.e. amount and rate) for plant uptake, growth and productivity on organic farms than conventional farms. The initial nutrient concentrations of leaf litter of organic cocoa systems were higher for S, Fe and Al compared to conventional systems. On annual basis, organic management enhances the release of primary and secondary macro-nutrients in the order K>N>P and S>Mg>Ca respectively than conventional management. This study demonstrates that organic management of cocoa agroforestry systems enhances leaf litter decomposition and nutrient mineralization and thereby makes essential nutrients available to plants for growth and productivity. Thus, organic management of cocoa agroforestry systems has the potential to contribute to sustainable cocoa production in smallholder systems.

6 INFLUENCE OF ORGANIC COCOA AGROFORESTRY ON SOIL PHYSICO-CHEMICAL PROPERTIES AND CROP YIELDS OF SMALLHOLDER COCOA FARMS, GHANA

Abstract

Cocoa is a major cash crop of most agrarian-based economies in West Africa. The success of sustainable cocoa production depends on the physical and chemical properties of the soils on which they are established but these are moderated by the management approach farmers adopt. The present study assessed and compared soil physico-chemical properties of organic and conventional cocoa agroforestry systems across three age groups (young, mature and old) at two depths (0-15 and 15-30 cm). It also evaluated the production of cocoa pods, banana and plantain in the two farm types. Cocoa farms under organic management had 20, 81, 88 and 323% higher stocks of soil organic carbon, P, Mn and Cu, respectively, compared to those under conventional management. Soil P stocks was positively correlated with shade tree basal area, Mn stocks to shade tree species diversity and Cu stocks to shade tree species density, basal area and richness. Soil moisture was 24% greater on organic farms than conventional but similar across cocoa temporal phases. Greater electrical conductivity was found in organic systems than the conventional farms. Annual cocoa pod production *per* tree was similar in both cocoa systems (Org. 10.1 ± 1.1 vs. Con. 10.1 ± 0.6 pods *per* tree) but with greater overall pod production in the conventional systems (Org. 9,560 ± 0.64 ha^{-1} yr^{-1} vs. Con. 12,433 ± 0.56 ha^{-1} yr^{-1}) due to greater cocoa tree density. The annual production of banana and plantain was higher on organic farms (186.3 ± 34.70 kg ha^{-1} yr^{-1}) than conventional systems (31.6

± 9.58 kg ha^{-1} yr^{-1}). It is concluded that organic management of cocoa systems have the potential to enhance soil quality and improve the production of by-products, therby diversifying farm output and farmers’ income. The study recommends the adoption of organic management in cocoa agroforestry systems and the provision of incentives to boost yields.

6.1 Introduction

Cocoa is a major export commodity of most agrarian-based economies in West Africa (Benefoh, 2018). Ghana is the second largest producer of cocoa in the world, with a cocoa industry worth over US $ 2 billion in 2016, directly employing more than 800,000 households and providing livelihoods for one-quarter of the nation’s populace (Ghana Cocoa Board, 2017; Benefoh, 2018). Cocoa production contributes 8-10 % to Ghana’s GDP and 30 % of total export earnings (Hütz-Adams *et al.*, 2016; Ghana Cocoa Board, 2017). Although Ghana and Côte d’Ivoire produce over 60 % of the world’s cocoa, productions in these countries are constrained by declining soil fertility which has resulted in poor cocoa yield (Wessel and Quist-Wessel, 2015; FAO, 2017). Declining soil fertility under cocoa farms have been cited as a driver of deforestation in Ghana as farmers tend to abandon old cocoa farms and establish new ones in existing forests (Gockowski and Sonwa, 2011; FAO, 2017). The regional frontiers of cocoa production in Ghana is associated with forest clearance by farmers in search of rich soils for the establishment of cocoa plantations (Knudsen and Agergaard, 2016; Benefoh, 2018). The success of sustainable cocoa production depends on the proper management of the physical and chemical properties of the soils on which they are established (Wood and Lass, 2001; van Vliet *et al.*, 2015).

Traditionally, cocoa is grown in a thinned forest forming a complex and multi-structural agroforestry system. Initially, the accumulated fertility of the forest soils plus nutrient inputs through the decomposition of litter from the system (i.e. cocoa and diverse trees) ensures cocoa production (Wessel and Quist-Wessel, 2015; Dawoe *et al.*, 2016). However continuous production without proper soil fertility management coupled with intensification (i.e. replacing the shade trees with cocoa trees to increase cocoa yield) leads to nutrient depletion and poor soil quality. Attempts to resolve this problem with synthetic chemical fertilizers has not been successful due to the socio-economic context of cocoa farmers (Barrientos *et al.*, 2008; Gockowski *et al.*, 2013; Hütz-Adams *et al.*, 2016). Cocoa is predominantly produced by poor rural smallholder farmers who are unable to access or afford synthetic fertilizers (Barrientos *et al.*, 2008; Hütz-Adams *et al*., 2016; Benefoh, 2018). As a result, over 50 % of the 1.63 million ha cocoa farms in Ghana do not use agrochemicals (Barrientos *et al.*, 2008; Gockowski *et al.*, 2013). Moreover, excessive use of synthetic agrochemicals is detrimental to soil biodiversity that underpin soil quality (Domínguez *et al.*, 2014).

Faced with the challenge of ensuring soil fertility and cocoa production in the current socio-economic context of cocoa farmers, organic cocoa farming seems promising. Organic farming, defined as a production system based on ecological processes and recycling with an inherent ethos to sustain the health of soils, ecosystems and people, have been shown to enhance soil physical, chemical and biological properties (Reganold, 1988; Aban, 2014; Lori *et al.,* 2017). However, robust data from West Africa are lacking and it is difficult to extrapolate from elsewhere due to regional and local/site-specific differences in soil composition and structure and the environmental conditions under which the soils were formed (van Vliet *et al.*, 2015). Moreover, cocoa agroforestry systems are complex dynamic systems with substantial structural and management differences at the local to regional scales, thus their impacts on soil fertility would vary. That notwithstanding, organic farming practices such as use of cover crops, leguminous plants, compost, farmyard manure and shade trees have been shown to improve soil fertility in a range of farming systems (Reganold, 1988; Lori *et al.,* 2017; Suja *et al.*, 2017), but the impact of organic management on soils of cocoa agroforestry systems is poorly understood. The non-use of synthetic agrochemicals alone was enough to maintain well-adapted soil biota (Domínguez *et al.*, 2014), which are critical for organic matter production through decomposition of litter inputs which might potentially influence soil physico-chemical properties.

Cocoa performs best in soils with 6.0-7.6 pH; alkaline soils make essential micro-nutrients such as Fe, Mn and Zn unavailable while highly acidic soils (pH < 4) induce deficiencies of Fe, Cu and Zn (Hardy, 1960; Landon, 2014; Ayorinde *et al.,* 2015). Furthermore, the minimum organic carbon content in the top 15 cm should be 1.5 % (i.e. > 3% organic matter) and the C:N ratio should range from 9-14, with a minimum N content of 0.18% (Sys *et al.*, 1993; Wood and Lass, 2001; Landon, 2014). Whereas a base saturation and cation exchange capacity of more than 35% and 12 cmol (+) kg^{-1}, respectively, are suitable for cocoa production, the exchangeable cations Ca, Mg and K must be greater than 8, 2 and 0.24 cmol (+) kg^{-1} soil respectively to ensure growth and yield (Hardy, 1960; Sys *et al.*, 1993; Landon, 2014; Ayorinde *et al.,* 2015). Additionally, the ratio of Ca:Mg must not exceed 4, (Ca + Mg):K must be greater than 25, and the ratio of the sum of the monovalent (K + Na) to the divalent (Ca + Mg) must not be higher than 1:50 (Hardy, 1960; Sys *et al.*, 1993).

Phosphorus availability is often limiting in West African soils because of its low content in soils, the influence of pH, iron, clay and organic carbon on its availability as well as greater fixation when phosphorus amendments are applied (Ahenkorah, 1981). Soils which support cocoa production should have 40 µg g^{-1} available phosphorus or more (Hardy, 1960). The availability of Ca, Mg and K depends on soil texture, clay soil have greater amounts of these nutrients than sandy soils (Ribon *et al.*, 2003; Aikpokpodion, 2010; Brito-Vega *et al.,* 2017). Benefoh (2018) reported a negative correlation between total N and clay content but a positive correlation between total N and soil organic carbon, highlighting the influence of these parameters on N mineralization and availability.

Given the nutritional requirements of cocoa, its sensitivity to nutrient deficiencies and the lack of robust data on soil physico-chemical properties of cocoa farms under organic and conventional management in West Africa, there is an urgent need to provide such data to guide decision making and policy formulations. Thus, the present study assessed and compared the physico-chemical properties of organic and conventional cocoa agroforestry systems across three age groups (young, mature and old) and explored the correlation between soil physical and chemical properties. Finally, cocoa pod, banana (*Musa sapientum* L. f. thomsonii King ex Baker) and plantain (*Musa paradisiaca* L.) production were examined in the two farm types as an assessment of productivity. Banana and plantain are important cash crops cultivated together with cocoa in the study area. It is posited in the present study that organic systems would manifest greater soil nutrient concentrations and stocks as well as cocoa pod, banana and plantain yields compared to conventional systems.

6.2 Methods

6.2.1 Study area

Suhum (Figure 2.1) has an agrarian economy based on rain-fed agriculture with cocoa being the main cash crop; other cultivated crops include banana (*M. sapientum*), plantain (*M. paradisiaca*) and cocoyam (*Cocos nucifera* L.). The description of the study area, cultivation practices and biophysical characteristics of the organic and conventional systems are presented in Chapter 1 (Page 3-6) and Chapter 2 (Page 30-47). The organic farms obtained their certification from Control Union, an international certification body that is present and active in over 70 countries.

6.2.2 Selection of cocoa farms

The plots of the present study have been described in detail in Chapter 2 (Page 30-33). In brief, Suhum Municipality was purposely selected because organic cocoa certification in Ghana was pioneered in the Municipality, thus it has the oldest certified organic cocoa farms. A list of organic and conventional cocoa farming communities within the Municipality was obtained from COCOBOD, the regulator of the cocoa sector in Ghana and seven cocoa communities were randomly selected (Figure 2.1). Separate lists of organic and conventional cocoa farmers in the selected communities were obtained from the local offices of the regulator and 24 cocoa farms under each of the two systems (i.e. 8 farms *per* farm type *per* cocoa temporal phase) were randomly selected for the study. The selected organic and conventional farms were categorised into three cocoa temporal phases, Young (≤ 15 years), Mature (16 to 30 years) and Old (≥ 31 years).

6.2.3 Data collection

6.2.3.1 Crop yield and stand characteristics

The methods which were used to collect stand characteristics (cocoa tree density and shade tree species density, basal area, richness and diversity) data have been described in Chapter 2 (Page 30-34). Cocoa yield was estimated in terms of cocoa pod production by counting the number of small (< 5 cm long), medium (5-10 cm) and large (> 10 cm) cocoa pods in August and January which coincides with the major and minor cocoa seasons respectively. The cocoa pod census was conducted in 25 m x 25 m plots established in the selected organic and conventional farms. The annual amount of banana (*M. sapientum*) and plantain (*M. paradisiaca*) production was estimated as the sum of the weight of each harvested bunch *per* farm over a 12-month period.

6.2.3.2 Soil sampling

Soil samples were collected from two depths (0-15 cm and 15-30 cm). In each plot and for each depth, five soil samples were collected using a soil auger. The five samples for each layer in each plot were pooled, thoroughly mixed and subsampled for chemical analysis. Two soil samples *per* plot *per* depth were collected with 139 cm^3 bulk density cylinders for soil bulk density determination. Soil samples were oven-dried (105° C for 48 hrs), sieved (2 mm mesh) and milled (Retsch agate ball mill at 290 rpm for 15 minutes) prior to chemical analysis.

6.2.4 Data processing and chemical analysis

6.2.4.1 Soil physical properties

Soil moisture content (%MC) was calculated as: $MC = [(S_1 - S_2)/S_2] \times 100$, where S_1 is the fresh weight of soil and S_2 is the weight of oven-dried (at 105° C for 48 hrs) soil. Soil bulk density was estimated as $BD\ (g\ cm^{-3}) = [(W_1 - W_2)/V] \times (100 - \%CF)/100$, where CF is coarse soil fraction, BD is bulk density, W_1 and W_2 are the weights of empty trays and oven-dried soils in trays respectively, and V is the volume of the bulk density cylinder. Soil particle size distribution was assessed via laser ablation (Bechman Coulter LS 200) and classified into textural classes based on the USDA soil triangle (Soil Survey Division Staff, 1993).

6.2.4.2 Soil chemical analysis

Soil pH was determined in a 1:2.5 soil:solution slurry with a pH meter (pH 209, Hanna Instruments), calibrated with pH 4.01 and 7.00 buffer solutions. The electrical conductivity (EC, mS cm^{-1}) of the soil was measured in the same soil slurry using a portable electrical conductivity meter (Combo pH and EC, Hanna Instruments) calibrated with 1413 µS cm^{-1} standard solution. To determine available P, soil samples (2 g) were extracted with 30 ml of 0.5 M sodium bicarbonate thoroughly mixed with 0.05 % w/v polyacrylamide, well shaken and centrifuged at 3500 rpm for 15 minutes. Phosphorus in the extract was estimated at 880 nm in a 1 cm cell using a spectrophotometer and the blue phospho-molybdate method with ascorbic acid as reducing agent. Total C and N were determined using a CN analyser (Thermo Scientific™ Flash™ 2000 Organic Elemental Analyzer (OEA)). Exchangeable Ca, Mg, K, and Na and the concentrations of Mn, Al, Cu and Zn were determined using ICP-MS (Thermo Scientific™ iCAP™ TQ) after extracting 2 g of each soil sample with 20 ml of 1 M NH_4NO_3, centrifuging at 3500 rpm for 30 minutes, filtering and diluting 1 ml of the supernatant with 9 ml of 2 % HNO_3. Effective cation exchange capacity (ECEC) was determined as the sum of exchangeable bases and exchangeable acidity. Nutrient stocks (Mg or kg ha^{-1}) were estimated as the product of nutrient concentration, bulk density, depth and unit conversion factor.

6.2.5 Statistical analysis of data

The fertility status of soils was assessed using the soil fertility threshold values required for cocoa production (Table 6.1). Yield data (cocoa, banana and plantain) were analysed via two-way ANOVA with farm type and cocoa temporal phase as the independent factors. Soil physical and chemical properties were analysed using general analysis of variance with farm type, cocoa temporal phase and soil depth as factors and plots as blocks. All variables, which were not normally distributed, were Box-Cox transformed to meet the normality assumption and those which remained non-normally distributed were analysed using Kruskal-Wallis ANOVA. Where interaction terms were not significant, only main effects were considered in results and discussion. Spearman's rank correlation was used to analyse the relationship between soil physico-chemical properties and nutrient concentrations as well as nutrient stocks, crop yield, and stand characteristics (cocoa tree density and shade tree species density, basal area, richness and diversity). Stand characteristics data have been presented in Chapter 2 (Pages 35-45). Differences in means were considered significant at $p < 0.05$.

Table 6.1: Soil requirements and nutrient thresholds for cocoa cultivation (0-15 cm layer)

Characteristic	**Soil suitability threshold**	**Source**
Coarse materials (%)	< 15	Ayorinde *et al.* (2015)
CEC (cmol (+) kg^{-1})	> 12	Hardy (1960); Sys *et al.* (1993)
Salinity (ds m^{-1})	< 1.8	Buggenhout (2018)
pH	6.0 – 7.6	Hardy (1960); Ayorinde *et al.* (2015)
Organic C (g kg^{-1})	> 15	Sys *et al.* (1993); Wood and Lass (2001)
N (g kg^{-1})	> 1.5	Sys *et al.* (1993); Landon (2014)
P (mg kg^{-1})	12-24	Wessel (1971)
Ca (cmol (+) kg^{-1})	≥ 8	Landon (2014); Buggenhout (2018)
Mg (cmol (+) kg^{-1})	≥ 2	Landon (2014); Buggenhout (2018)
K (cmol (+) kg^{-1})	≥ 0.24	Landon (2014); Buggenhout (2018)

6.3 Results

6.3.1 Soil physical properties

The moisture contents of the soils were influenced by farm type, depth and their interaction but not the temporal phase of cocoa. Soil moisture was 24 % greater on organic farms than conventional farms ($F_{1, 42} = 13.58$, $p < 0.001$) and 19 % higher in topsoil compared to subsoil ($F_{1, 42} = 87.23$, $p < 0.001$) (Table 6.2). Soil coarse content was significantly higher on conventional farms compared to organic farms ($F_{1, 42} = 4.52$, $p = 0.039$), subsoil compared to topsoil ($F_{1, 42} = 8.39$, $p = 0.006$) and marginally significant for cocoa temporal phases ($F_{2, 42} = 3.21$, $p = 0.051$). Soil bulk density was similar for both farm types and cocoa temporal phases, but increased with depth ($F_{1, 42} = 45.80$, $p < 0.001$). Clay, silt and sand contents were independent of farm management type, cocoa temporal phase and soil depth; soils in both organic and conventional farms were classified as loamy for the 0-30 cm depth.

Table 6.2 Selected soil physical properties (Mean ± SEM) of topsoil (0-15 cm) and subsoil (15-30 cm) of young (≤ 15 years), mature (16 to 30 years) and old (≥ 31 years) organic (Org.) and conventional (Con.) cocoa agroforestry systems at Suhum.

		Young		**Mature**		**Old**	
Parameter	**Depth (cm)**	**Org.**	**Con.**	**Org.**	**Con.**	**Org.**	**Con.**
Clay (%)	0-15	11.27 ± 2.08	13.58 ± 2.78	10.31 ± 2.48	9.1 ± 3.12	14.12 ± 1.99	17.91 ± 4.61
	15-30	13.67 ± 2.46	11.41 ± 3.59	10.63 ± 2.07	8.9 ± 1.93	14.98 ± 2.67	14.86 ± 4.29
Silt (%)	0-15	41.6 ± 4.27	48.96 ± 7.78	46.23 ± 6.27	35.58 ± 5.94	52.76 ± 4.94	46.35 ± 6.9
	15-30	46.92 ± 4.92	38.35 ± 7.73	52.49 ± 5.69	37.37 ± 4.61	52.8 ± 6.12	39.72 ± 6.68
Sand (%)	0-15	47.13 ± 6.11	37.46 ± 10.3	43.49 ± 8.15	55.33 ± 8.72	33.13 ± 6.4	35.73 ± 10.89
	15-30	39.42 ± 7.06	50.23 ± 11.13	36.88 ± 7.21	53.73 ± 6.2	32.23 ± 8.46	45.42 ± 10.56
Moisture content (%)	0-15	32.69 ± 2.7	22.44 ± 1.79	33.7 ± 2.71	25.21 ± 2.07	34.13 ± 1.5	27.89 ± 2.62
	15-30	25.78 ± 1.12	19.97 ± 1.65	25.42 ± 1.84	22.75 ± 1.87	27.11 ± 0.89	26.01 ± 2.49
Bulk density (g cm^{-3})	0-15	1.2 ± 0.11	1.07 ± 0.06	1.29 ± 0.1	1.11 ± 0.06	1.08 ± 0.05	1.13 ± 0.09
	15-30	1.21 ± 0.1	1.14 ± 0.07	1.56 ± 0.14	1.21 ± 0.05	1.24 ± 0.04	1.23 ± 0.08
Coarse content (%)	0-15	9.4 ± 2.51	12.99 ± 2.19	4.47 ± 0.62	10.42 ± 2.53	9.18 ± 2.31	11.25 ± 3.21
	15-30	16.9 ± 3.62	21.44 ± 4.26	6.86 ± 1.5	12.93 ± 2.95	11.69 ± 1.96	10.45 ± 2.4
Soil type	0-30	Loam	Loam	Loam	Sandy loam	Silt loam	Loam

6.3.2 Soil chemical properties

The effect of farm type on soil electrical conductivity was more pronounced than pH (Table 6.3). Both pH ($F_{1, 46}$ = 6.74, p = 0.013) and electrical conductivity ($F_{1, 42}$ = 9.06, p = 0.004) were higher on organic farms than conventional farms and decreased with soil depth (pH; $F_{1, 42}$ = 11.27, p = 0.002; EC, $F_{1, 42}$ = 65.70, $p < 0.001$). There was a significant interaction of farm type and soil depth ($F_{1, 42}$ = 10.34, p = 0.003) on soil electrical conductivity; Fisher's protected LSD showed that the topsoils of organic systems had greater electrical conductivity than the soils of the conventional systems but the electrical conductivity of the subsoils of both farm types were similar. Effective cation exchange capacity was similar for cocoa farms under organic and conventional management, increased from young cocoa farms to mature and old farms (df = 2, H = 7.917, p = 0.019) and decreased with soil depth (df = 1, H = 7.271, p = 0.007). The ratios C:N, Ca:Mg, Ca+Mg:K and Ca+Mg:Na+K were similar for both farm types, cocoa temporal phases and soil depths. Exchangeable cations (Na^+, Mg^{2+}, Ca^{2+} and K^+) were similar on both farm types.

Table 6.3 Selected soil chemical properties (Mean ± SEM) in topsoil (0-15 cm) and subsoil (15-30 cm) of young (≤ 15 years), mature (16 to 30 years) and old (≥ 31 years) organic (Org.) and conventional (Con.) cocoa agroforestry systems at Suhum.

		Young		**Mature**		**Old**	
Parameter	**Depth (cm)**	**Org.**	**Con.**	**Org.**	**Con.**	**Org.**	**Con.**
pH	0-15	6.73 ± 0.1	6.81 ± 0.23	7.19 ± 0.22	6.32 ± 0.12	7.13 ± 0.15	6.78 ± 0.16
	15-30	6.4 ± 0.15	6.63 ± 0.24	6.79 ± 0.25	6.32 ± 0.17	6.97 ± 0.18	6.74 ± 0.16
EC (mS cm^{-1})	0-15	0.19 ± 0.02	0.14 ± 0.02	0.15 ± 0.02	0.11 ± 0.01	0.22 ± 0.03	0.12 ± 0.03
	15-30	0.1 ± 0.01	0.09 ± 0.01	0.1 ± 0.02	0.09 ± 0.01	0.15 ± 0.02	0.11 ± 0.02
Effective CEC cmolC kg^{-1}	0-15	9.35 ± 1.43	8.64 ± 1.23	12.22 ± 1.33	12.33 ± 2.52	13.75 ± 1.96	11.1 ± 1.78
	15-30	6.22 ± 0.52	7.36 ± 1.14	10.13 ± 1.45	9.69 ± 1.93	8.96 ± 1.28	9.61 ± 1.79
Ca:Mg ratio	0-15	7.96 ± 0.58	6.09 ± 0.44	8.22 ± 0.98	7.3 ± 1.2	8.5 ± 1.46	7.5 ± 1.18
	15-30	8.7 ± 0.61	6.58 ± 0.83	7.06 ± 0.5	7.31 ± 0.88	9.64 ± 2.00	7.98 ± 1.44
(Ca+Mg):K Ratio	0-15	20.85 ± 3.98	23.57 ± 4.07	29.68 ± 3.43	28.71 ± 5.88	27.53 ± 3.15	23.45 ± 4.46
	15-30	22.22 ± 2.6	23.18 ± 3.95	25.53 ± 1.8	26.19 ± 4.06	26.72 ± 3.77	21.19 ± 3.57
(Ca+Mg):(K +N) ratio	0-15	18.4 ± 3.21	18.7 ± 2.49	26.49 ± 2.94	23.92 ± 4.21	24.91 ± 2.73	20.15 ± 4.17
	15-30	17.72 ± 1.73	18.2 ± 2.1	22.37 ± 1.93	22.04 ± 3.01	23.38 ± 3.15	19.09 ± 3.11
C:N ratio	0-15	7.81 ± 0.88	8.09 ± 1.41	10.49 ± 0.74	11.65 ± 2.16	9.88 ± 1.17	7.87 ± 1.82
	15-30	15.12 ± 7.36	8.57 ± 2.25	9.71 ± 1.09	8.45 ± 1.89	13.14 ± 3.28	11.53 ± 1.74

6.3.3 Soil nutrient concentrations

Farm management type, cocoa temporal phase, soil depth and their interaction affected soil nutrient concentrations. Whilst the concentration of P ($F_{1\ 42}$ = 23.61, $p < 0.001$) and Mn (df = 1, H = 13.00, $p < 0.001$) were 64-66 % higher on organic farms compared to conventional farms, it was 200 % greater for Cu ($F_{1,\ 39}$ = 27.22, $p < 0.001$) (Figure 6.1). Mature and old cocoa farms had a greater (33-61 %) concentration of P ($F_{2\ 42}$ = 5.04, $p = 0.011$), a lower (30-60 %) concentration of Mn (df = 2, H = 9.811, $p = 0.007$) and a similar concentration of Cu compared to young farms. The concentrations of P and Cu decreased with soil depth (P, $F_{1\ 42}$ = 21.96, $p < 0.001$; Cu, $F_{1,\ 34}$ = 25.67, $p < 0.001$) and Mn remained the same for both soil depths.

Soil total N contents were similar between farm types and across cocoa temporal phases but decreased with soil depth; soil organic carbon also decreased with soil (SOC, df = 1, H = 13.05, $p < 0.001$; total N, $F_{1,\ 42}$ = 106.03, $p < 0.001$). The interactive effect of farm type and soil depth on soil organic carbon content was significant ($F_{1,\ 42}$ = 4.19, $p = 0.047$) and so was the interactive effect of farm type, soil depth and cocoa temporal phase ($F_{2,\ 42}$ = 3.79, $p = 0.031$); Fisher’s protected LSD indicated that the topsoils of old organic cocoa systems had higher (45 %) soil organic carbon content than the topsoils of young conventional cocoa systems. Both organic and conventional cocoa systems had similar concentrations of Ca, Mg and K. Topsoil had greater concentrations of K ($F_{1, 42} = 32.89$, $p < 0.001$), Mg ($F_{1, 42} = 64.53$, $p < 0.001$) and Ca ($F_{1, 42} = 3.21$, $p < 0.001$) than subsoil. Zn concentration was independent of both farm type and soil depth but depended on cocoa temporal phase ($F_{2\ 39} = 4.49$, $p = 0.018$).

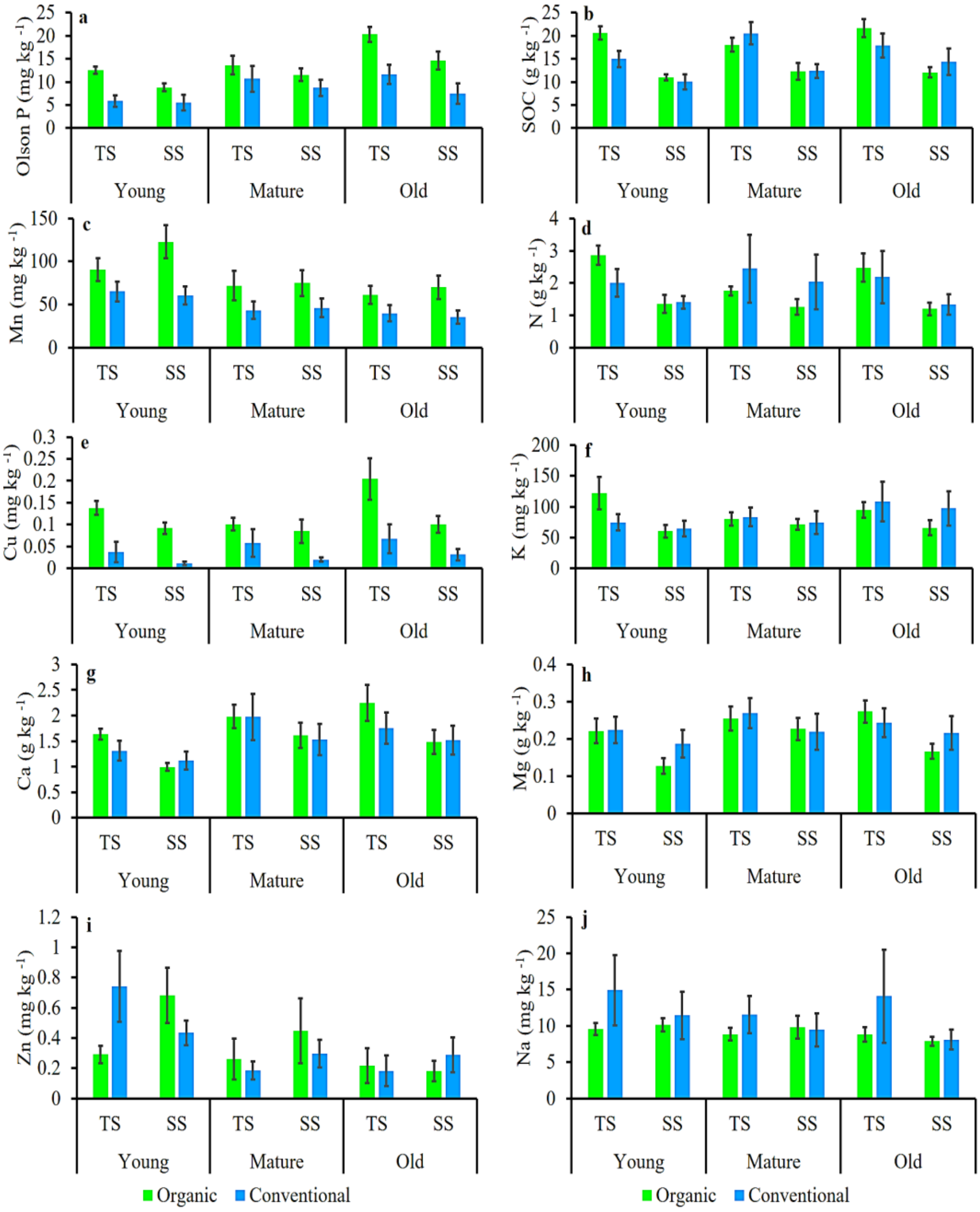

Figure 6.1 Mean (± SEM) nutrient concentration in topsoil (TS, 0-15 cm) and subsoil (SS, 15-30 cm) of young (≤ 15 years), mature (16 to 30 years) and old (≥ 31 years) organic (Org.) and conventional (Con.) cocoa agroforestry systems at Suhum. Panels a-j represent P, soil organic carbon (SOC), Mn, N, Cu, K, Ca, Mg, Zn and Na respectively.

6.3.4 Correlations between nutrient concentrations and selected soil chemical and physical properties

Soil bulk density was negatively related to percentage clay, percentage silt, moisture content, electrical conductivity, pH, soil organic carbon and the concentrations of K and Mg, but it positively correlated with percentage sand (Table 6.4). Moisture content was positively associated with Ca, Mg, K, Mg, P and soil organic carbon (SOC). While soil electrical conductivity was positively related to Ca, K, Mg and P contents as well as SOC and total N, pH was positively associated with Ca, Mg and P as well as effective cation exchange capacity but negatively related to Mn. Soil organic carbon content was positively related to the concentration of the nutrients Ca, K, Mg and P, and clay content.

Table 6.4 Spearman's rank correlation coefficients of selected soil physico-chemical properties and nutrient concentrations. BD (bulk density, g cm^{-3}), MC (moisture content), Clay, Silt and Sand (all in %), EC (electrical conductivity, mS cm^{-1}), ECEC (Effective Cation Exchange Capacity, cmolC kg^{-1}), Mg, soil organic C (SOC), TN (total N) and Ca (all in g kg^{-1}), and K, P (available P) and Mn (all in mg kg^{-1}).

	BD	**Ca**	**Clay**	**EC**	**ECEC**	**K**	**Mg**	**Mn**	**MC**	**P**	**pH**	**Sand**	**Silt**
BD	1												
Ca	-0.192	1											
Clay	-0.383**	0.14	1										
EC	-0.339**	0.542**	0.287**	1									
ECEC	-0.183	0.975**	0.132	0.515**	1								
K	-0.243*	0.662**	0.098	0.405**	0.688**	1							
Mg	-0.245*	0.759**	0.188	0.36**	0.828**	0.681**	1						
Mn	0.031	-0.507**	0.164	-0.186	-0.484**	-0.312**	-0.199	1					
MC	-0.427**	0.346**	0.543**	0.578**	0.337**	0.32**	0.347**	0.165	1				
P	-0.051	0.67**	0.096	0.438**	0.635**	0.546**	0.503**	-0.249*	0.362**	1			
pH	-0.037	0.44**	-0.03	0.646**	0.415**	0.194	0.206*	-0.454**	0.192	0.384**	1		
Sand	0.311**	-0.164	-0.91**	-0.22*	-0.17	-0.174	-0.284**	-0.228*	-0.503**	-0.131	0.029	1	
Silt	-0.277**	0.172	0.826**	0.193	0.186	0.2	0.321**	0.23*	0.455**	0.153	-0.011	-0.976**	1
SOC	-0.328**	0.735**	0.21*	0.583**	0.734**	0.637**	0.679**	-0.183	0.498**	0.515**	0.193	-0.2	0.179
TN	-0.075	0.276**	0.004	0.306**	0.278**	0.185	0.19	0.012	0.104	0.228*	0.053	0.102	-0.135

*$p < 0.05$, ** $p < 0.01$

6.3.5 Soil nutrient stocks

Cocoa farms under organic management had 20, 81, 88 and 323 % higher stocks of soil organic carbon ($F_{1, 42} = 4.50$, $p = 0.040$), P ($F_{1, 42} = 25.17$, $p < 0.001$), Mn ($F_{1, 42} = 12.71$, $p < 0.001$) and Cu ($F_{1, 39} = 28.46$, $p < 0.001$), respectively, compared to those under conventional management (Figure 6.2). The stocks of soil organic carbon was 45 % greater in topsoil than subsoil and similar across the different cocoa temporal phases, P was 16 % greater in topsoil than subsoil ($F_{1\ 42} = 4.99$, $p = 0.031$) and 44-54 % greater on mature and old cocoa farms compared to young systems ($F_{2, 42} = 4.69$, $p = 0.014$), and Mn was 19 % higher in subsoil than topsoil ($F_{1\ 42} = 5.77$, $p = 0.021$) and similar across cocoa temporal phases. Soil depth had a significant influence on Cu stocks ($F_{1\ 34} = 17.80$, $p < 0.001$).

Cocoa farms under organic management had similar N, Ca, Mg and K stocks as those under conventional management and there were no differences in mean stocks of these nutrients across cocoa temporal phases. However, N stocks decreased with soil depth (df = 1, H = 9.070, $p = 0.003$) and so was Mg ($F_{1\ 42} = 9.89$, $p = 0.003$), Ca ($F_{1\ 42} = 9.81$, $p = 0.003$) and K ($F_{1\ 42} = 10.14$, $p = 0.003$). Both Zn and Na stocks were independent of farm type and cocoa temporal phase but whereas Zn stocks increased with soil depth ($F_{1\ 37} = 4.21$, $p = 0.047$), Na stocks showed no significant differences.

Spearman’s rank correlation of soil nutrient stocks and stand characteristics (cocoa and shade tree species densities, and shade tree species basal area, richness and diversity) showed that P was negatively related to cocoa density ($r^2 = -0.300$, $p = 0.038$) and positively correlated with shade tree basal area ($r^2 = 0.416$, $p = 0.003$). Mn was positively correlated with shade tree species diversity (Shannon diversity) ($r^2 = 0.269$, $p = 0.046$) while Cu was negatively related to cocoa tree density ($r^2 = -0.290$, p = 0.0.046) but positively correlated with shade tree species density ($r^2 = 0.296$, $p = 0.041$), basal area ($r^2 = 0.523$, $p < 0.001$) and richness ($r^2 = 0.309$, $p = 0.033$).

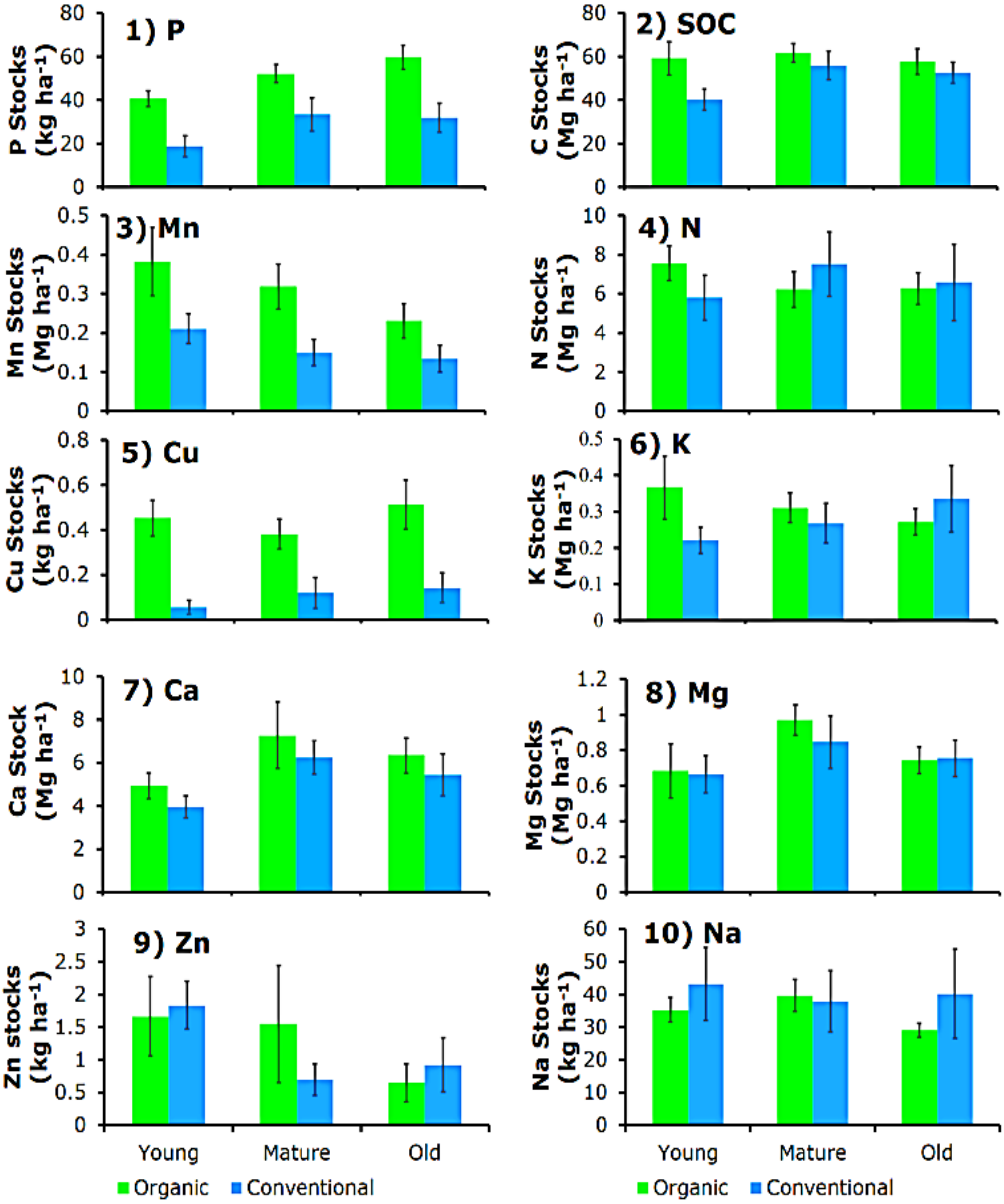

Figure 6.2 Nutrient stocks (Mean ± SEM) to the depth 0-30 cm in young (≤ 15 years), mature (16 to 30 years) and old (≥ 31 years) organic and conventional cocoa agroforestry systems at Suhum. The panels 1-10 represent P, soil organic carbon (SOC), Mn, N, Cu, K, Ca, Mg, Zn and Na respectively.

6.3.6 Crop yield

Although the production of medium, large and total (sum of small, medium and large) cocoa pods were 28, 58 and 30 % respectively greater on conventional cocoa farms than organic cocoa systems (Figure 6.3a, $p < 0.05$), the production of these cocoa pods *per* tree were similar (10 pods *per* tree) between organic and conventional farms. The mean annual production of banana was 570 % greater in cocoa systems under organic management compared to those under conventional management (Figure 6.3b, $F_{1, 42} = 26.64$, $p < 0.001$). However, plantain production was similar in both farm types. The total annual production of banana and plantain was 490 % greater on organic farms than conventional farms (Figure 6.3b, $F_{1, 42} = 25.20$, $p < 0.001$).

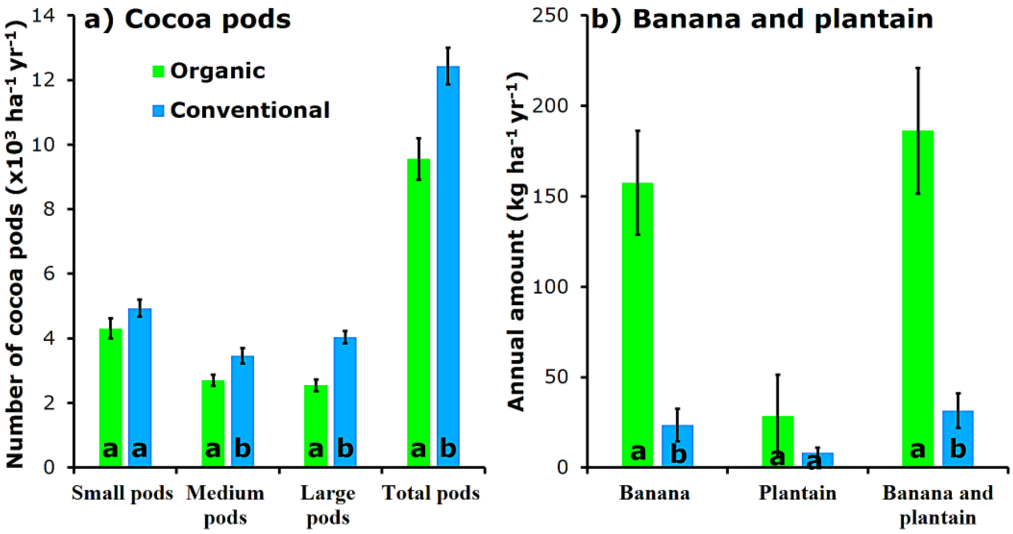

Figure 6.3 Annual cocoa pod, banana and plantain production (Mean ± SEM) in organic and conventional cocoa agroforestry systems at Suhum. Small (< 5 cm), medium (5-10 cm), large (> 10 cm) and total (sum of small, medium and large).

Spearman’s rank correlation of total cocoa pod production and annual banana and plantain yield with stand characteristics and soil nutrient stocks showed that annual banana and plantain yield was positively correlated to P (r^2 = 0.335, p = 0.020) and Cu (r^2 = 0.432, p = 0.002) stocks. Shade tree basal area (r^2 = 0.518, p < 0.001) and fruit species density (r^2 = 0.680, p < 0.001) positively correlated with annual banana and plaintain yield, but cocoa tree density was negatively related to banana and plaintain yield (r^2 = -0.413, p = 0.004). Total cocoa pod production was negatively correlated to Cu stocks (r^2 = -0.335, p = 0.020) and shade tree species basal area (r^2 = -0.367 p = 0.010).

6.4 Discussion

6.4.1 Effect of organic management on selected soil physical properties

The results showed that soil moisture content was greater (24 %) in organic systems than conventional systems and decreased (by 19 %) with soil depth as reported by other workers (Reganold, 1988; Suja *et al.*, 2017; Di Prima *et al.*, 2018). In Chapter 2 (Page 37-48) greater shade tree species richness and diversity were found on organic farms than conventional farms thus micro-climatic conditions moderated by the presence of diverse shade trees may lead to reduced evapotranspiration rate which in turn improves soil moisture content. Although there exists a potential for belowground competition for water and aboveground competition for light, planting deep rooting and deciduous shade tree species coupled with canopy management (e.g. regular pruning) would minimise these negative effects. Furthermore, the greater amount of coarse content in the soils under conventional management than organic farms (Table 6.2) reduces their capacity to hold soil water (Wessel 1971) and may explain the differences in soil moisture contents. Cocoa is sensitive to drought hence high moisture-holding capacity is crucial in regions with pronounced dry seasons, such as the study area (Wessel 1971; Beer, 1987; Kyereh, 2017); the organic farms are promising in this context.

Both the organic and conventional cocoa agroforestry systems had similar proportions of sand, silt and clay and were characterized as having loamy soils (Table 6.2), suggesting that the soils were formed from similar parent material and under uniform environmental conditions, unaffected by management practices at the moment (Dawoe *et al.*, 2014; Okoffo *et al.,* 2016; Benefoh *et al.*, 2018). Bulk density, which is an indication of soil structure, influences root growth and the flow of oxygen and water through the soil (Brito-Vega *et al.*, 2018; Di Prima *et al.*, 2018). The similar soil bulk densities in organic (1.28 ± 0.04 g cm^{-3}) and conventional (1.15 ± 0.04 g cm^{-3}) systems are attributable to the fact that cocoa agroforestry systems use minimum tillage, which does not affect soil bulk density (Brito-Vega *et al.*, 2018). The results are similar to and fall within the critical bulk density (BD) range ($0.9 \leq BD \leq 1.2$ g cm^{-3}) for optimum crop growth and production (Suja *et al.*, 2017;

Benefoh *et al.*, 2018; Brito-Vega *et al.*, 2018; Di Prima *et al.*, 2018).

6.4.2 Effect of farm management type on selected soil chemical properties

Cocoa farms under organic management had higher (39%) electrical conductivity than those under conventional management, indicating greater potential for nutrient uptake since increasing electrical conductivity when it is below the range 1-4 dS m^{-1} means higher amount of nutrients availability for crop uptake (Table 6.3; Heinen *et al.,* 2002; Aban, 2014; Buggenhout, 2018). Electrical conductivity (EC) is an indicator for soil health, suggesting an improved soil health for the organic farms. EC influences crop yields as well as the activity of soil microorganisms, which play a critical role in nutrient recycling (Heinen *et al.,* 2002; Aban, 2014; Brito-Vega *et al.*, 2018). Soil EC depends on several factors such as soil texture, moisture, cation exchange capacity and pH as well as Mg and Ca contents (Table 6.4; Peralta and Costa, 2013). Therefore, the greater levels of soil moisture and P concentration on organic farms than conventional farms as well as their interaction with other physico-chemical properties may explain the differences in mean electrical conductivity (Peralta and Costa, 2013). Even though the pH values for both farm types are consistent with the optimum range (6.0 - 7.6) required for cocoa production (Table 6.1; Hardy, 1960; Ayorinde *et al*., 2015; Buggenhout, 2018), organic management enhanced soil pH at the 0-15 cm depth than conventional management. Contrary to the report that cocoa cultivation leads to soil acidification, i.e. lowering of pH (e.g. Ahenkorah *et al.,* 1987; Hartemink, 2005), the results showed that pH remained similar across the different cocoa temporal phases (Table 6.3) which is consistent with other workers (Ofori-Frimpong *et al.*, 2007; Arévalo-Gardini *et al*., 2015). The integration of woody plants with dense and deep root system captures leached nutrients and return them to the soil through litterfall and decomposition thereby offering a buffer capacity, which maintains soil pH across the different productive cocoa phases (Arévalo-Gardini *et al.,* 2015). Furthermore, abundant litter on the floor, a characteristic of cocoa systems, acts as a permanent soil cover thereby reducing nutrient loss through surface run-offs and leaching (Dawoe *et al.*, 2014; Arévalo-Gardini *et al*., 2015).

The similar exchangeable cations (Na^+, Mg^{2+}, Ca^{2+} and K^+) and effective cation exchange capacity (ECEC) between organic and conventional farms is consistent with literature (Cornwell, 2014). ECEC estimates the capacity of the soil to absorb and release cations hence the greater the ECEC the greater the ability of the soil to replace nutrients lost through leaching and plant uptake (Cornwell, 2014). Therefore, ECEC is an indication of mineral soil fertility, which in turn depends on soil texture and organic matter content (Ayorinde *et al.,* 2015; Brito-Vega *et al.*, 2018).

The exchangeable cations Ca^{2+} and Mg^{2+} on both organic and conventional farms were above the critical values (7.5 and 1.33 cmol (+) kg^{-1}, respectively) whilst K^{+} was slightly below the critical value (0.24 cmol (+) kg^{-1}) for cocoa production (Table 6.1; Ahenkorah, 1981; Arthur *et al.*, 2017), thus additional supply of K is needed on both farm types to ensure continuous sustainable cocoa production. The near deficiency levels of K can be overcome by the application of manure, cocoa pod husk ash and incorporation of pruned materials coupled with management practices, which protect the soil from all forms of leaching and erosion (van Vliet *et al.,* 2015; Arthur *et al.,* 2017). The fact that the ratios C:N, Ca+Mg:K and Ca+Mg:Na+K in both organic and conventional systems were similar and consistent with the critical values (9-14, ≥ 25 and ≤ 50, respectively) needed for cocoa production (Hardy, 1960; Sys *et al.*, 1993), indicates their potential for sustainable cocoa production.

6.4.3 Effect of farm management type on the concentrations and stocks of soil nutrients

The results generally support what was postulated in the present study that organic farms would manifest greater nutrient concentrations and stocks than conventional farms. Cocoa farms under organic management had greater concentrations and stocks of the macro-nutrient P compared to those under conventional management (Figures 6.1 and 6.2); this corroborates with literature (Aban, 2014; Suja *et al.* 2018) and the P values were adequate for cocoa agroforestry systems assuming a required P of 12-24 mg kg^{-1}

(Wessel 1971). Adequate P is important for increased cocoa root development, which in turn increases the capacity of cocoa trees to absorb nutrients for growth and productivity (van Vliet *et al.,* 2015). West African soils are reported to contain low P, limiting its availability to plants (Boyer, 1973; Ahenkorah, 1981) but organic management of cocoa agroforestry systems demonstrates the potential to enhance its availability possibly due to increased P mineralization resulting from greater soil moisture content (Table 6.2), diverse litter as a result of diverse shade tree species (Chapter 2, Pages 37-48) and well-adapted soil biota (Domínguez *et al.*, 2014). The fact that P stocks was positively correlated with shade tree basal area but negatively related to cocoa tree density indicates the role shade tree species play in contributing to P stocks in the two systems through litterfall (Chapter 4, Pages 97-103). Furthermore, P availability in the soil depends on several factors such as concentrations of Ca, Mg, K and soil organic C, total N and pH (Table 6.4; Ahenkorah, 1981); the interactive effect of these factors together with the greater electrical conductivity in organic systems possibly explains the greater availability of P on organic farms.

The similar but slightly lower concentrations and stocks of K on both farms types than the amount required for proper cocoa growth and yield (Ahenkorah, 1981; Arthur *et al.*, 2017) is possibly due to greater immobilization in tree biomass and continual losses through cocoa beans production (Hartemink, 2005; Aikpokpodion, 2010;

Arévalo-Gardini *et al.,* 2015). Moreover, K plays a critical role in the synthesis of carbohydrates hence cocoa trees demand high quantities of it (Chacin *et al*., 1999). The nutrient K is rapidly mineralized during litter decomposition because it is a non-structural element thus additional supply of this nutrient could be made available for plant uptake through the application of manure and compost (Boyer, 1973; van Vliet *et al.,* 2015).

The ability of cocoa systems to capture and retain atmospheric N depends on the type and composition of shade tree species, soil characteristics, plantation management approach and history, and topography (van Vliet *et al.,* 2015; Brito-Vega *et al.*, 2018). The N content in the soils of both farm types corroborate with literature and were consistent with the minimum amount of N (0.18 %) needed for cocoa production (Wood and Lass, 2001; van Vliet *et al.,* 2015). N is important for cocoa leaf flushing and canopy formation. The fact that organic cocoa farms maintained similar concentrations and stocks of total N as that of the conventional farms without synthetic agrochemicals (Figures 6.1 and 6.2) show their potential for sustainable cocoa production. In their review, Hartemink (2005) reported N in annual litterfall to be 20-45 and 2-3 % of the total N in the vegetation and soils respectively, that is, N returns through litterfall could be responsible for its adequate stocks in the two farm types. Soil organic carbon (SOC) which is an important indicator of soil fertility was consistent with the critical value (1.5 %) for cocoa production (Buggenhout, 2018).

Whereas Ca plays a key role in root turgor and osmotic pressure, the interaction of which determines the loss, gain or maintenance of cell water (Turner, 2018), Mg is important for cocoa leaf retention due to its role as a critical component in the structure of every molecule of chlorophyll (van Vliet *et al.,* 2015). The Ca and Mg values were consistent with literature and suitable for cocoa production (Wessel, 1971).

According to Boyer (1973), 30-year-old cocoa trees required 3-4, 0.1, 4-5, 4.5-6 and 1-1.5 kg ha^{-1} yr^{-1} of N, P, K, Ca and Mg respectively for growth. Landon (2014) estimated that to produce 560 kg ha^{-1} of dry beans, which is relatively closer to the average cocoa yield of 450 kg ha^{-1} in Ghana, the nutrient uptake of the crop is 25 kg ha^{-1} N, 4.5 kg ha^{-1} P, and 36 kg ha^{-1} K. Based on these figures and assuming similar nutritional demand and cocoa planting density, the nutrient stocks reported in the present study (Figure 6.2) could sustain cocoa growth and production for several years with P and K contents possibly being the main limiting factors, which can be minimised through the incorporation of cocoa pod husk compost and wood ash (Boyer, 1973; van Vliet *et al.,* 2015; Kongor *et al.,* 2018). Nutrient recycling through litterfall, root turnover and rainwash may potentially reduce the limiting effect of P and K contents (van Vliet *et al.,* 2015), making the systems sustainable in the long run without synthetic fertilizers.

Organic management enhanced the concentrations and stocks of the micro-nutrients Mn and Cu compared to those under conventional management (Figure 6.2) possibly due to greater mobilization of these nutrients through litter decomposition on the organic farms (Figure 5.2; Table 5.2; Chapter 5, Page 135-136) or greater immobilization in cocoa trees on conventional farms (Arévalo-Gardini *et al*., 2015). The combined effect of micro-nutrient scarcity in the soil and other factors such as pH affects their availability for uptake by plants and their deficiencies in African soils have been reported (Baligar *et al*., 2006; Zingore *et al*., 2008). Organic management demonstrates the potential to increase the availability of micro-nutrients especially Cu and Mn probably as a result of the use of manure or compost from organic residues such as cocoa pod husks (Zingore *et al*., 2008; van Vliet *et al*., 2015; Buggenhout, 2018). Furthermore, the fact that Mn as positively correlated with shade tree species diversity and Cu was positively related to shade tree species density, basal area and richness shows the importance of rich and diverse shade tree species in increasing the availability of micro-nutrients. Even though organic farms were not receiving synthetic chemical fertilizers, their soil nutrient stocks were similar to or greater than the conventional farms and this is possibly linked to the greater quantity and quality of litter deposition from highly diverse shade tree species (Mamani-Pati *et al.*, 2012; Fontes *et al.*, 2014).

6.4.4 Farm management type and crop yield

The results demonstrate that although total cocoa pod production was 30 % lower in organic systems compared to conventional farms, cocoa pod production *per* tree was similar on both farms, which indicates that the greater total cocoa pod production on conventional farms was due to differences in cocoa tree density (Figure 6.3a; Chapter 2, Page 37-48). Moreover, the fact that total cocoa pod production was negatively correlated to shade tree species basal area suggests that conventional cocoa farmers replaced shade tree species with cocoa trees, which resulted in an overall greater cocoa pod production. Schneider *et al.* (2017) reported similar cocoa yield on both organic and conventional agroforestry farms whilst Jacobi *et al.* (2015) reported greater yields in organic agroforestry systems compared to conventional systems. Organic farmers on the other hand had 490 % greater annual banana and plantain yield compared to conventional farmers indicating potential for a more diversified approach to cocoa production (Figure 6.3b; Jacobi *et al.,* 2015). Therefore, the hypothesis of finding greater banana and plantain production on organic farms than conventional farms was supported by the results, but the results did not support the posit that cocoa pod production will be greater on organic farms.

The idea that organic farmers sought to diversify farm output is confirmed by the significant positive correlation of annual banana and plantain production with shade tree species basal area and fruit species density and its negative correlation with cocoa tree density. That is whereas conventional cocoa farmers replaced shade tree species with cocoa trees, organic farmers incorporated more fruit species and shade tree species. Other workers have described organic farming as climate smart (Bandanaah *et al.*, 2014) and resilient farming systems (Jacobi *et al.*, 2015) due their greater crop and shade tree species diversity. The production of co-products such as banana and plantain which has the potential to diversify income and reduce shocks is important in the discussion about adaptation to climate change and climate change mitigation (Kremen and Miles, 2012; Bandanaah *et al.*, 2014; Jacobi *et al.*, 2015; Schneider *et al.,* 2017).

6.5 Conclusions

Organic management of cocoa agroforestry systems enhanced the moisture content and chemical properties of the soil than conventional management. The soils of both organic and conventional cocoa agroforestry systems had high nutritional content and were suitable for sustainable cocoa production, but this was more so on the organic systems than the conventional farms even though organic farms were not receiving synthetic fertilizers. Organic cocoa producers diversified farm output by incorporating more shade tree and fruit species which resulted in greater annual banana and plantain production whiles conventional farmers replaced shade tree and fruit species with cocoa trees which resulted in greater total cocoa pod production. It was concluded that organic management of cocoa agroforestry systems result in soils with greater overall quality for cocoa production than conventional management and that it increases the yield of co-products. The study recommends the adoption of organic cocoa production as it maintains soil quality without affecting cocoa pod production *per* tree. However, incentives should be provided for organic farmers to increase cocoa pod production *per* tree in order to boost or maintain their interest in organic cocoa farming.

7 GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

7.1 Introduction

Cocoa cultivation has transformed the semi-deciduous vegetation of the study area into patches of secondary forests and fallows and continues to do so. To mitigate against further deforestation and protect ecosystem services, it is critical to adopt innovative approaches to ensure cocoa production and environmental sustainability. This study aimed at providing data on the potential of organic cocoa agroforestry systems to contribute to sustainable land management. To do this, tree diversity, nutrient recycling, soil quality and cocoa pod production were assessed in organically and conventionally managed cocoa systems.

7.2 General discussion: organic management and sustainable land management

The results presented in this thesis highlights the potential of organic management of cocoa systems to contribute to sustainable land management through tree species conservation, carbon sequestration, efficient nutrient recycling and enhanced soil quality (i.e. physico-chemical properties).

Results in Chapter 2 showed that cocoa agroforestry systems of the study area included a rich list of shade tree species on their farms of which 95 % were native species thus emphasizing their role in the conservation of native floristic diversity and their ecological importance as the dominant species (Anglaaere *et al.*, 2011; Bandanaa *et al*., 2014; Dawoe *et al.*, 2016; Mbolo *et al.*, 2016).

Organic management supported greater shade tree species richness, diversity and basal area than conventional management even though both farm types had similar total tree density (shade trees plus cocoa), which is in line with literature (Bandanaa *et al*., 2014; Jacobi *et al.*, 2015). Organic cocoa cultivation in the study area encourages the use of shade trees to improve soil fertility (Chapter 1, Table 1.1). Annual nutrients deposition through litterfall (Table 4.4), justifies the inclusion of a range of native shade tree species on organic farms (Mamani-Pati *et al.*, 2012). Therefore, organic management practices such as prohibiting the use of synthetic chemical fertilizers to maintain soil fertility in cocoa systems whilst encouraging the use of shade trees as an alternative (Table 1.1) accounted for the rich and diverse shade tree species found on the organic farms (Bandanaa *et al*., 2014; Jacobi *et al.*, 2015).

The contribution of litterfall from shade trees to annual nutrients return (Chapter 4, Figure 4.4; Table 4.4) coupled with enhanced litter decomposition and nutrient mineralisation in organic cocoa systems (Chapter 5, Table 5.2; Fließbach *et al.*, 2000; Vazquez *et al.* 2003) possibly accounted for the improved soil nutrient concentrations and stocks in organically managed soils (Chapter 6; Figure 6.1-6.2; Hartemink, 2005; Mamani-Pati *et al.*, 2012; Fontes *et al.*, 2014). For example, soil P stocks were positively correlated with shade tree basal area, Mn stocks to shade tree species diversity and Cu stocks to shade tree species density, basal area and richness (Section 6.3.5). Therefore, shade trees are major sources of nutrients in cocoa systems (Mamani-Pati *et al.*, 2012; Fontes *et al.*, 2014) and management approach regulates their potential.

A major potential constraint pointed out in the literature in relation to the inclusion of shade trees in cocoa farms and organic management has been yield losses (Wade *et al.*, 2010; Asare *et al.*, 2017). The results from this study (Chapter 6, Section 6.3.6) indicate that cocoa pod production *per* tree was similar for both farm types but conventional farms tended to have greater overall cocoa pod production due to greater cocoa tree density. The overall stem densities (cocoa plus shade trees and fruits) were similar for both farm types, but annual banana and plantain production in the organic cocoa systems was five times greater than conventional systems (Org. 186.3 kg ha^{-1} yr^{-1} vs. Con. 31.6 kg ha^{-1} yr^{-1}). This is possibly a reflection of an attempt by organic farmers to diversify farm output, spread risk and generate additional income (Kremen and Miles, 2012; Bandanaah *et al.*, 2014; Jacobi *et al.*, 2015), an approach which is generally advocated for under current and predicted future tropical climatic conditions. Moreover, the results indicated that organic farms have greater potential to generate additional income from sale of carbon credits than conventional systems (Org. 74.58 - 208.07 US$ ha^{-1} yr^{-1} vs. Con. 39.08 - 99.60 US$ ha^{-1} yr^{-1}). Therefore, organic premiums, income from co-products and incentives from carbon schemes may potentially compensate for yield losses if any (Beer *et al.,* 1998; Armengot *et al.,* 2016; Schneider *et al.,* 2017). In discussing strategies to enhance the potential of smallholder cocoa agroforestry systems to contribute to sustainable land management, organic management is a critical factor.

7.3 Major conclusions and recommendations

This study deepens current knowledge and understanding of the impact of management approach on cocoa ecosystems across different temporal phases. It has added to knowledge on the diversity and ecological importance of shade tree species on cocoa farms at different productive stages. It has provided data on nutrient deposition via litterfall and decomposition over time on organic and conventional cocoa systems. Data on the potential of organic and conventional cocoa systems to sustain soil quality and contribute to climate change mitigation through carbon sequestration has also been provided. The results of this study also support existing data provided by other workers in similar ecosystems.

7.3.1 Conclusions

The results of this study form the basis of the following conclusions:

(i) Organic cocoa agroforests are more tree biodiverse than conventional cocoa agroforests. This implies that organic management is a resilient farming approach that conserve biodiversity compared to conventional management.

(ii) Floristic compositions are dissimilar on organic and conventional cocoa farms and the dissimilarity increases across productive cocoa stages driven by intensification. This means that the composition of shade tree species across cocoa productive phases is closely linked to management approach.

(iii) Tree species with an economic value are the most important shade-providing species in smallholder cocoa systems. Both organic and conventional management of cocoa systems favours pioneer forest tree species and fruit trees and crops.

(iv) Organic management is a crucial tool to capture and store carbon in smallholder cocoa agroforestry systems, sequestering 3.4 – 9.0 Mg C ha^{-1} yr^{-1} (vegetation plus soils) with potential to generate additional income (74.58 - 208.07 US\$ ha^{-1} yr^{-1}) through the sale of carbon credits. The main driver of vegetation carbon stocks in cocoa systems were shade trees moderated by farm management approach.

(v) The shade tree species that had high ecological importance values on both organic and conventional cocoa farms were at the same time the shade tree species that contributed highly to biomass carbon stocks. This means shade tree species dominancy regulates their contribution to biomass carbon stock.

(vi) Cocoa systems under organic management produced similar number of cocoa pods *per* tree as conventional farms with an additional 186 kg ha^{-1} yr^{-1} of banana and plantain. Management approach affects cocoa tree density, which in turn regulates overall cocoa pod production in smallholder shade-cocoa systems.

(vii) Cocoa agroforestry systems under organic management maintains soil physico-chemical properties suitable for cocoa growth and production with a potential to increase the nutrient stocks of available P and stocks of the micro-nutrients Mn and Cu.

(viii) Organically managed cocoa farms demonstrated greater potential to efficiently recycle both macro- and micro-nutrients via litterfall and decomposition than conventional farms. Thus, organic shade-cocoa systems have the potential to be productive without external nutrient inputs.

(ix) The nutrient K may potentially limit cocoa production in smallholder systems. Levels of this nutrient in the soil of the cocoa farms was marginally insufficient, indicating a potential inability of these systems to meet K requirements for cocoa production in future.

(x) Shade trees play a complementary role in macro- and micro-nutrient deposition in smallholder cocoa farms, contributing 30-47 % of annual nutrient return through litterfall (except Ni, Zn and Co) in organic cocoa systems and 20-35 % in conventional cocoa systems.

7.3.2 Recommendations

To meet sustainable land management goals in smallholder cocoa systems, the following recommendations are made:

(i) Adoption of organic management in smallholder cocoa systems. Organic farms showed greater potential to capture and store carbon, conserve tree biodiversity and recycle nutrients than conventional farms and at the same time produce similar cocoa pod yield *per* tree as conventional farms. Therefore, it is recommended that smallholder cocoa farmers be encouraged to integrate organic management practices into their cocoa systems as it ensures systems’ sustainability.

(ii) Integration of shade trees. Shade trees played a critical role in vegetation carbon storage and a significant complementary role in nutrient recycling, especially in organic systems. Enhancing the nutrient recycling potential of smallholder farmers is crucial to their sustainability and this can be achieved through the maintenance of shade trees. Thus, their inclusion in smallholder cocoa systems is highly recommended.

(iii) Provision of incentives. Since annual cocoa pods production were lower in organic systems, it is necessary to boost farmers’ interest in maintaining highly tree biodiverse cocoa farms by providing incentives to compensate for loses in overall cocoa yield if any. Linking organic farmers to organic markets for banana and plantain as well as carbon credit markets may help organic farmers to generate additional income.

(iv) Inclusion of smallholder organic cocoa systems in national carbon management activities aiming at enhancing carbon storage. With the greater potential to sequester carbon in vegetation and soil pools than conventional systems, including smallholder organic cocoa agroforestry systems in national carbon management activities is highly recommended.

(v) Enhancement of K stocks. With marginally deficient levels of K in soils of the cocoa systems, additional supply of this nutrient is recommended to ensure sustainable cocoa production in the long term. Farmers can achieve this through the application of cocoa pod husks compost or ash.

(vi) Enhancement of pod production *per* tree. Organic farmers are encouraged to pursue management strategies aimed at enhancing cocoa pod production *per* tree. This can be achieved through pruning, manuring and enhanced sanitary measures. Enhancing cocoa pod production *per* tree may translate into overall cocoa pod yields, which are comparable to those achieved in the conventional systems.

7.4 Future research recommendations

This research has provided quantitative data on tree diversity, carbon stocks, soil quality and nutrient recycling in organic and conventional cocoa agroforestry systems. To further deepen the general understanding of cocoa agroforestry systems and their contribution to environmental sustainability, the following recommendations are made for future research:

(i) In Chapter 2, information on the diversity and importance value of shade trees in organic and conventional cocoa agroforestry systems was provided. It is important to explore the contribution of shade trees to smallholder cocoa farmers' income. This will deepen the general understanding of the economic importance of shade trees and provide information on total system output. Furthermore, the composition, diversity and activity of soil biota, and how farm management type affects these features over time could be a focus of future research. It is also critical to understand the potential of the cocoa systems to support above- and below-ground fauna diversity.

(ii) This study quantified and compared vegetation and soil organic carbon stocks in the two cocoa systems (Chapter 3), it is recommended that future studies should investigate carbon stocks in deeper depths (> 30 cm) and carbon emissions in these systems to provide a complete model on net carbon capture and storage by the cocoa systems. It is critical to know the mechanisms driving carbon emissions in the two farm types.

(iii) A scientific assessment of soil quality (physico-chemical properties) was undertaken in this research and the data is presented in Chapter 6. An understanding of farmers' perception and assessment of soil quality would provide information on cumulated local knowledge on soil fertility.

It is important to know what indicators farmers use to assess the fertility and quality of the soils on their cocoa farms and which indictors produce results similar to technical methods. Thus, future research should evaluate soil quality from farmer's perspective.

(iv) Soil nutrient concentrations and stocks have been reported here for the cocoa systems up to 30 cm depth. Future studies could focus on deeper depths (> 30 cm), and the role of deep-rooting shade trees in pontentially 'mining' nutrients from deeper depths.

(v) Data on nutrient return via litterfall and decomposition was investigated in this study (Chapter 4 and 5). However, baseline information on the contribution of fine roots to nutrient return, the timing of their production and mortality as well as the mechanisms driving these is important to complement the data provided in this study. Furthermore, studies on the contribution of N-fixing shade tree species to nutrient recycling would determine their potential role in sustaining smallholder cocoa production.

(vi) Although cocoa pod production has been evaluated in the cocoa systems (Chapter 6), a study relating dry cocoa bean quality and organic management practices will provide complementary results.

(vii) Linking cocoa yields with farmers’ socio-economic characteristics would also be important to understand the main socio-economic drivers of cocoa yields in the cocoa systems.

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APPENDIX TABLES AND FIGURES

Appendix Table 1: List of shade species and their abundance in studied cocoa systems

		Species category	**Relative Abundance (% *per* ha)**					
			YCS		**MCS**		**OCS**	
Family	**Species**		**Con.**	**Org.**	**Con.**	**Org.**	**Con.**	**Org.**
Fabaceae	*Albizia adianthifolia* (Schum.) W.Wight	Planted legume				0.3		
Fabaceae	*Albizia ferruginea* (Guill. and Perr.) Benth.	Forest tree						0.3
Fabaceae	*Albizia glaberrima* (Schumach. and Thonn.) Benth.	Forest tree	0.5	0.2				
Fabaceae	*Albizia zygia* (DC.) J.F.Macbr.	Forest tree		0.4	0.6	1.3		0.7
Apocynaceae	*Alstonia boonei* De Wild.	Forest tree		0.9		1.3		2
Fabaceae	*Amphimas pterocarpoides* Hams	Forest tree				0.5		0.3
Sapotaceae	*Aningeria robusta* Aubrev. et Pellegr.	Forest tree						0.3
Loganiaceae	*Anthocleista nobilis* G. Don	Forest tree		0.4			0.9	0.3
Moraceae	*Antiaris toxicaria* Lesch.	Forest tree	1.5	0.2			3.5	
Anacardiaceae	*Antrocaryon micraster* A.Chev.	Forest tree	0.5					
Moraceae	*Artocarpus altilis* (Parkinson) Fosberg	Forest tree	0.5			0.8		
Sapindaceae	*Blighia sapida* K.D.Koenig	Forest tree	0.5					
Sapindaceae	*Blighia unijugata* Baker	Forest tree				0.3		
Euphorbiaceae	*Bridelia grandis* Pierre ex Hutch.	Forest tree	1.5					0.7
Caricaceae	*Carica papaya* L	Fruit plant	2	0.2	0.6	0.5	0.9	1
Meliaceae	*Cedrela odorata* L.	Planted tree					0.9	
Ulmaceae	*Celtis mildbraedii* Engl.	Forest tree		0.2				
Sapotaceae	*Chrysophyllum subnudum* (Bak.)	Forest tree				0.3		0.7
Rutaceae	*Citrus aurantifolia* (Christm.) Swingle	Fruit tree	2					
Rutaceae	*Citrus sinensis* (L.) Osbeck	Fruit tree		3.7	4.4	1	2.6	3.3

Appendix Table 1 continued

Annonaceae	*Cleistopholis patens* (Benth.) Engl. and Diels	Forest tree			0.6	0.3		0.7
Arecaceae	*Cocos nucifera* (L.)	Fruit tree	0.5				3.5	
Sterculiaceae	*Cola gigantea* A.Chev.	Forest tree					1.8	
Boraginaceae	*Cordia millenii* Baker	Forest tree				0.3		
Ebenaceae	*Diospyros abyssinica* (Hiern) F. White	Forest tree						0.3
Euphorbiaceae	*Discoglypremna caloneura* (Pax) Prain	Forest tree				0.5		
Caesalpiniaceae	*Distemonanthus benthamianus* Baill.	Forest tree				0.3		
Boraginaceae	*Ehretia trachyphylla* C.H.Wright	Forest tree	0.5		1.7			0.3
Meliaceae	*Entandrophragma angolense* (Welw.) C.DC.	Forest tree		0.7		2.6		1
Fabaceae	*Erythrina vogelii* Hook f.	Forest tree	0.5	0.7		0.3		
Moraceae	*Ficus capensis* Thunb.	Forest tree		0.2				
Moraceae	*Ficus exasperata* Vahl	Forest tree	2	1.1	1.7	0.3	1.8	1.7
Moraceae	*Ficus lutea* Vahl	Forest tree				0.3		0.3
Moraceae	*Ficus sur* Forssk	Forest tree		1.1	0.6	1	1.8	0.7
Moraceae	*Ficus vogeliana* (Miq.) Miq.	Forest tree	0.5	0.2		0.3		
Moraceae	*Ficus vogelii* (Miq.) Miq.	Forest tree	0.5	0.2				0.3
Apocynaceae	*Funtumia africana* (Benth.) Stapf.	Forest tree	0.5				0.9	0.7
Fabaceae	*Gliricidia sepium* (Jacq.) Walp.	Planted legume	1.5	1.1		0.3		0.3
Simaroubaceae	*Hannoa klaineana* Pierre et Engl.	Forest tree						0.3
Apocynaceae	*Holarrhena floribunda* (G. Don) Dur and Schinz	Forest tree	11.6	0.7	6	1.3	0.9	1.7
Bignoniaceae	*Kigelia africana* (Lam.) Benth.	Forest tree						0.7
Anacardiaceae	*Lannea welwitschii* (Hiern) Engl.	Forest tree		0.7				
Fabaceae	*Leucaena leucocephala* (Lam.) de Wit.	Planted legume						0.3
Fabaceae	*Lonchocarpus sericeus* (Poir.) Kunth ex DC.	Forest tree			2.8		2.6	
Anacardiaceae	*Mangifera indica* L.	Fruit tree	0.5	0.7	0.6	0.8		1.3
Sterculiaceae	*Mansonia altissima* (A.Chev.) A.Chev.	Forest tree			0.6	0.5		
Euphorbiaceae	*Margaritaria discoidea* (Baill.) Webster	Forest tree					0.9	
Euphorbiaceae	*Mareya micrantha* (Benth.) Müll.Arg.	Forest tree		0.2				

Appendix Table 1 continued

Moraceae	*Milicia excelsa* (Welw.) C.C.Berg	Forest tree	0.5	0.2	0.6		2.6	
Moraceae	*Milicia regia* (A.Chev.) Berg	Forest tree	1	0.7	0.6	1.6		0.7
Fabaceae	*Millettia zechiana* Harms	Forest tree	3.5		1.1		3.5	
Rubiaceae	*Morinda lucida* Benth.	Forest tree	10.6	1.5	1.7	1	0.9	3
Moraceae	*Morus mesozygia* Stapf.	Forest tree			0.6			
Musaceae	*Musa paradisiaca* L.	Fruit plant	14.7	13.7	5.5	2.1	14.9	2.3
Musaceae	*Musa sapientum* L. f. thomsonii King ex Baker	Fruit plant	21.2	60.8	52.2	72	38.6	67.6
Sterculiaceae	*Nesogordonia papaverifera* (Chev, A.) Cap.	Forest tree	0.5	0.2	0.6	0.8		
Bignoniaceae	*Newbouldia laevis* (P. Beauv.) Seemann ex Bureau	Forest tree	2	2	0.6	0.5		0.3
Lauraceae	*Persea americana* Mill.	Fruit tree	3.5	0.7	0.6	1.3	1.8	2
Fabaceae	*Piptadeniastrum africanum* (Hook.f.) Brenan	Forest tree				0.5		0.3
Anacardiaceae	*Pseudospondias microcarpa* (A.Rich.) Engl.	Forest tree			0.6	0.3		
Myrtaceae	*Psidium guajava* (L.)	Fruit tree	1					
Sterculiaceae	*Pterygota macrocarpa* K.Schum.	Forest tree		0.2				
Myristicaceae	*Pycnanthus angolensis* (Welw.) Warb.	Forest tree	1	0.2	0.6	0.3		
Apocynaceae	*Rauvolfia vomitoria* Afzel	Forest tree	2.5	0.4	1.1	0.8	1.8	0.3
Euphorbiaceae	*Ricinodendron heudelotii* (Baill.) Pierre ex Heckel	Forest tree			0.6	0.5	0.9	0.3
Solanaceae	*Solanum erianthum* D. Don	Forest tree				0.3		
Bignoniaceae	*Spathodea campanulata* P. Beauv.	Forest tree	2	0.7	1.1		0.9	0.3
Anacardiaceae	*Spondias mombin* L.	Forest tree	0.5	0.4			5.3	
Sterculiaceae	*Sterculia rhinopetala* K.Schum.	Forest tree		0.2				
Sterculiaceae	*Sterculia tragacantha* Lindl.	Forest tree	1	1.1	0.6	0.3		
Sapotaceae	*Synsepalum dulcificum* (Schum. and Thonn.) Daniell	Forest tree		0.2				
Combretaceae	*Terminalia catappa* L.	Forest tree			0.6			
Combretaceae	*Terminalia ivorensis* (A. Chev.)	Forest tree	0.5	1.8		1.8	2.6	1.3
Combretaceae	*Terminalia superba* Engl. and Diels	Forest tree	1		1.7	0.5		0.7
Fabaceae	*Tetrapleura tetraptera* (Schum. and Thonn.) Taub.	Forest tree			0.6			0.3

Appendix Table 1 continued

Euphorbiaceae	*Tetrorchidium didymostemon* (Baill.) Pax and K.Hoffm.	Forest tree			0.6	0.3	
Ulmaceae	*Trema orientalis* L.	Forest tree		0.2			
Meliaceae	*Trichilia monadelpha* (Thonn.) J.J.de Wilde	Forest tree		0.4	0.6	0.3	
Meliaceae	*Trichilia tessmannii* Harms	Forest tree					0.9
Moraceae	*Trilepisium madagascariense* D.C.	Forest tree			0.6		
Sterculiaceae	*Triplochiton scleroxylon* K.Schum.	Forest tree					0.2
Compositae	*Vernonia amygdalina* Delile	Forest tree					0.9
Apocynaceae	*Voacanga africana* Stapf	Forest tree	5.1	0.2	7.1		1.8

Appendix Table 2: Ecological importance of the ten most abundant shade species in organic and conventional farms across the different cocoa-age groups. R.A. is relative abundance, R.D is relative dominance, R.F. is relative frequency and IVI is importance value index.

Cocoa-age group	**Species**	**R.A. (% *per* ha)**	**R.D. (% *per* ha)**	**R.F. (% *per* ha)**	**IVI**
Organic YCS	*Musa sapientum* L. f. thomsonii King ex Baker	60.79	38.77	13.54	113.1
	Musa paradisiaca L.	13.66	7.43	5.21	26.29
	Newbouldia laevis (P. Beauv.) Seemann ex Bureau	1.98	3.06	6.25	11.29
	Citrus sinensis (L.) Osbeck	3.74	1.94	5.21	10.9
	Spathodea campanulate P. Beauv.	0.66	6.74	3.13	10.53
	Terminalia ivorensis (A. Chev.)	1.76	3.14	4.17	9.07
	Ficus exasperate Vahl	1.1	2.62	5.21	8.93
	Mangifera indica L.	0.66	4.37	3.13	8.15
	Sterculia tragacantha Lindl.	1.1	3.83	3.13	8.06
	Morinda lucida Benth.	1.54	2.73	3.13	7.4
Conventional YCS	*Musa sapientum* L. f. thomsonii King ex Baker	21.21	11.77	8.54	41.52
	Holarrhena floribunda (G. Don) Dur and Schinz	11.62	12.69	10.98	35.28
	Morinda lucida Benth.	10.61	13.16	8.54	32.3
	Musa paradisiaca L.	14.65	6.5	4.88	26.02
	Citrus aurantifolia (Christm.) Swingle	2.02	9.84	3.66	15.51
	Persea americana Mill.	3.54	3.91	3.66	11.1
	Millettia zechiana Harms	3.54	1.36	6.1	11
	Voacanga africana Stapf	5.05	3.33	2.44	10.82
	Ficus exasperata Vahl	2.02	2.1	4.88	9
	Carica papaya L.	2.02	1.79	4.88	8.69
Organic MCS	*Musa sapientum* L. f. thomsonii King ex Baker	72.02	38.6	15.22	125.84
	Terminalia ivorensis (A. Chev.)	1.81	9.08	4.35	15.24
	Entandrophragma angolense (Welw.) C.DC.	2.59	5.97	6.52	15.09
	Ficus sur Forssk	1.04	7.01	4.35	12.4
	Magnifera indica L.	0.78	4.76	3.26	8.8
	Milicia regia (A.Chev.) Berg	1.55	3.5	3.26	8.32

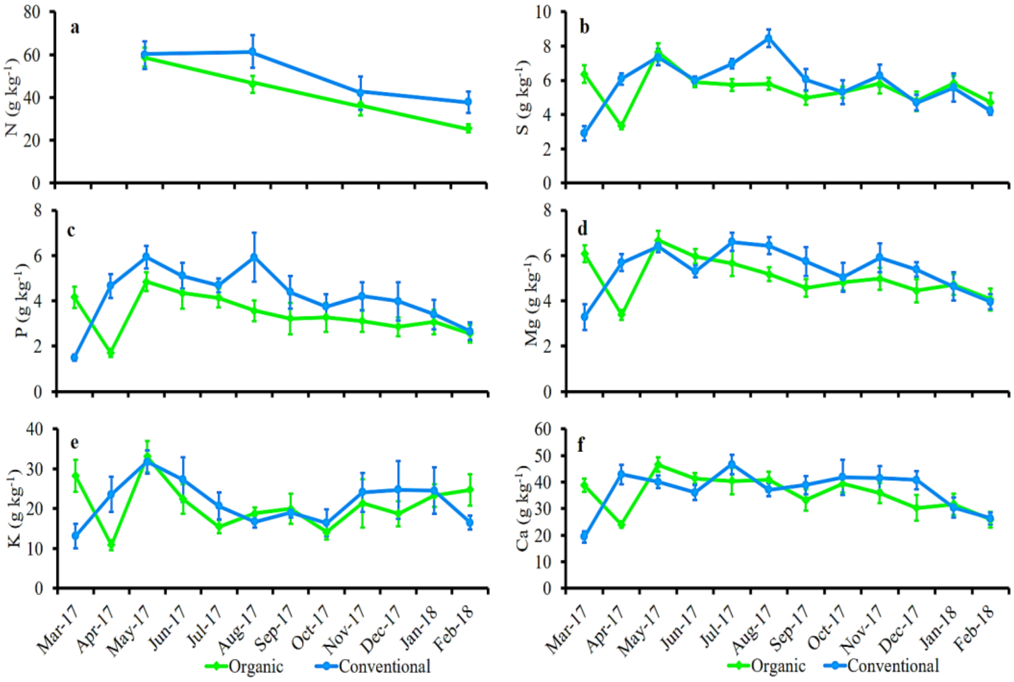
Appendix Table 2 continued					
	Persea americana Mill.	1.3	2.19	4.35	7.83
	Musa paradisiaca L.	2.07	1	4.35	7.42
	Morinda lucida Benth.	1.04	1.64	4.35	7.03
	Alstonia boonei De Wild.	1.3	2.17	3.26	6.73
Conventional MCS	Musa sapientum L. f. thomsonii King ex Baker	52.2	24.67	11.86	88.74
	Voacanga africana Stapf	7.14	5.78	10.17	23.1
	Lonchocarpus sericeus (Poir.) Kunth ex DC.	2.75	15.53	3.39	21.67
	Holarrhena floribunda (G. Don) Dur and Schinz	6.04	7.2	6.78	20.03
	Citrus sinensis (L.) Osbeck	4.4	6.19	3.39	13.98
	Musa paradisiaca L.	5.49	2.35	5.08	12.93
	Ficus exasperata Vahl	1.65	4.23	3.39	9.26
	Spathodea campanulata P. Beauv.	1.1	5.03	1.69	7.82
	Terminalia superba Engl. and Diels	1.65	1.28	3.39	6.31
	Rauvolfia vomitoria Afzel	1.1	1.81	3.39	6.3
Organic OCS	Musa sapientum L.	67.56	31.23	17.28	116.08
	Alstonia boonei De Wild.	2.01	10.3	3.7	16.01
	Citrus sinensis (L.) Osbeck	3.34	2.32	7.41	13.07
	Morinda lucida Benth.	3.01	4.97	4.94	12.92
	Magnifera indica L.	1.34	7.42	3.7	12.46
	Milicia regia (A.Chev.) Berg	0.67	7.42	2.47	10.56
	Persea americana Mill.	2.01	1.88	6.17	10.06
	Holarrhena floribunda Pierre et Engl.	1.67	2.02	3.7	7.4
	Musa paradisiaca L.	2.34	1.27	3.7	7.31
	Terminalia ivorensis (A. Chev.)	1.34	2.76	2.47	6.57
Conventional OCS	Musa sapientum L. f. thomsonii King ex Baker	38.6	17.4	14.58	70.58
	Musa paradisiaca L.	14.91	5.32	12.5	32.73
	Antiaris toxicaria Lesch.	3.51	10.32	4.17	17.99
	Cola gigantea A.Chev.	1.75	13.12	2.08	16.96
	Terminalia ivorensis (A. Chev.)	2.63	4.85	6.25	13.73
	Cocos nucifera (L.)	3.51	6.01	4.17	13.69
	Lonchocarpus sericeus (Poir.) Kunth ex DC.	2.63	4.73	4.17	11.52
	Spondias mombin L.	5.26	2.65	2.08	10
	Milicia excelsa (Welw.) C.C.Berg	2.63	2.03	4.17	8.83
	Ficus exasperata Vahl	1.75	2.87	4.17	8.79

Appendix Table 3: The number and stem density of shade species used for domestic, ecological and economic purposes

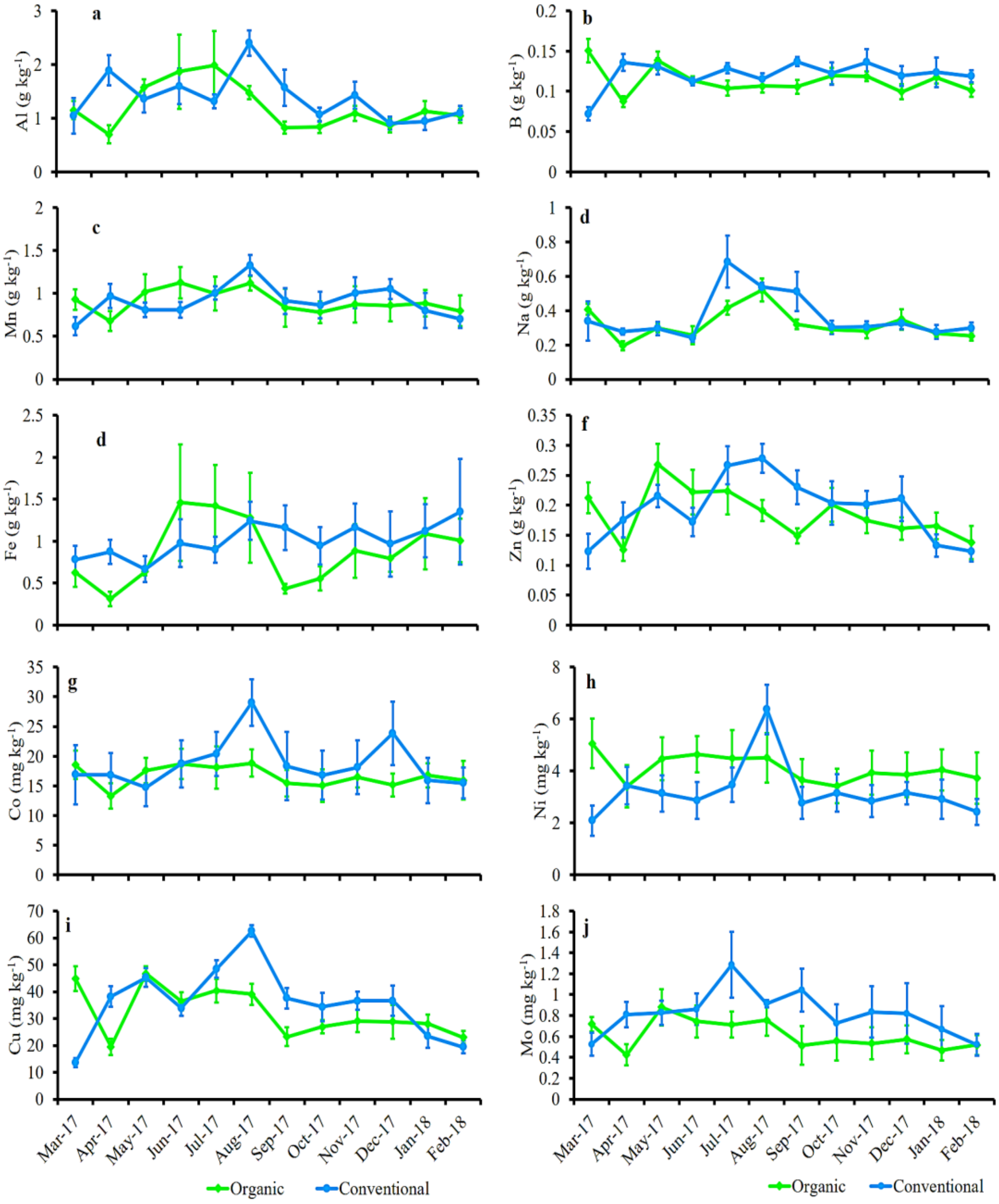
		Tree use group		
Cocoa age group	**Farm type**	**Domestic**	**Ecological**	**Economic**
Number of shade species				
YCS	Organic	10	13	18
	Conventional	14	10	17
MCS	Organic	9	11	18
	Conventional	8	12	15
OCS	Organic	13	5	17
	Conventional	9	5	13
Shade species stem density				
YCS	Organic	44.57	30.86	443.43
	Conventional	35.43	18.29	388.57
MCS	Organic	35.43	23.00	284.57
	Conventional	66.29	26.29	122.29
OCS	Organic	33.14	11.43	163.43
	Conventional	17.14	17.14	96.00

Appendix Table 4: Repeated measures ANOVA of the concentrations of monthly nutrient deposition and farm type. 'a' degree of freedom is $F_{1, 14}$ for all parameters except C and N ($F_{1, 10}$); 'b' degree of freedom is $F_{11, 154}$ for all parameters except C and N ($F_{3, 30}$). The degrees of freedom were multiplied by the Greenhouse-Geisser epsilon values (GGE) before the estimation of p-values shown in parenthesis and significant values ($p < 0.05$) are italicised.

Parameter	Nutrient deposition (g kg^{-1} mon^{-1})	GGE	Farm type	Month	Farm type x Month
Primary macro-nutrients	C	0.8252	0.01 (0.915)	25.94 (< *0.001*)	3.48 (*0.038*)
	N	0.9088	2.72 (0.130)	13.74 (< *0.001*)	0.90 (0.444)
	P	0.4254	2.93 (0.109)	6.56 (< *0.001*)	5.03 (< *0.001*)
Secondary macro-nutrients	K	0.5243	0.00 (0.975)	4.49 (< *0.001*)	3.62 (< *0.001*)
	Mg	0.4689	2.03 (0.176)	5.34 (< *0.001*)	4.47 (< *0.001*)
	Ca	0.4519	0.20 (0.663)	5.73 (< *0.001*)	4.93 (< *0.001*)
	S	0.4941	1.20 (0.292)	9.46 (< *0.001*)	6.80 (< *0.001*)
Micro-nutrients	Na	0.5255	0.51 (0.487)	9.75 (< *0.001*)	2.32 (*0.043*)
	Al	0.5125	4.27 (0.058)	3.92 (*0.002*)	2.77 (*0.019*)
	Mn	0.5252	0.01 (0.913)	2.87 (*0.015*)	2.07 (0.069)
	Fe	0.5014	2.83 (0.114)	1.64 (0.154)	1.44 (0.215)
	B	0.5258	0.98 (0.339)	1.51 (0.187)	6.55 (< *0.001*)
	Co	0.4200	0.09 (0.772)	1.26 (0.291)	0.82 (0.531)
	Ni	0.4109	1.00 (0.336)	3.49 (*0.010*)	3.28 (*0.013*)
	Cu	0.4685	1.72 (0.210)	11.78 (< *0.001*)	8.79 (< *0.001*)
	Zn	0.4279	0.11 (0.747)	4.77 (*0.001*)	3.21 (*0.013*)
	Mo	0.5123	1.58 (0.229)	3.69 (*0.003*)	2.36 (*0.041*)



Appendix Figure 1: Macro-nutrient concentrations of monthly litterfall of organic and conventional cocoa agroforestry systems at Suhum. Panels a-f represent N, S, P, Mg, K and Ca (g kg^{-1}), respectively.



Appendix Figure 2: Concentration micro-nutrients in monthly litterfall of organic and conventional cocoa agroforestry systems at Suhum. Panels a-j represent Al, B, Mn, Na, Fe, Zn (all in g kg^{-1}), Co, Ni, Cu and Mo (all in mg kg^{-1}), respectively.